Mestrado Integrado em Engenharia Química

Properties of Asymmetrically Twisted Cords for Tire Reinforcements

Master Thesis

by

Luisa Cristina da Costa Couto

Performed at

Indústria Têxtil do Ave - Continental

Supervisor at FEUP: **Prof. Adélio Mendes**

Industrial Supervisor: **Eng. Alexandre Gomes**

Dr. Thomas Kramer

Universidade do Porto

Faculdade de Engenharia

FEUP

Departamento de Engenharia Química

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Abstract

The tire is responsible for establishing the contact point between the road and the vehicle. The tire is made of materials that go beyond just rubber, such as metallic and textile reinforcement parts. The most common used textile materials in the tire industry are nylon, polyester, aramid and rayon. Those fiber materials are long continuous length of interlocked filaments or yarns, and they are twisted to form a cord. This project is a research on the construction of the cord made from the textile materials and it presents a first attempt to study the asymmetric construction.

The project took place at Continental – Indústria Têxtil do Ave, S.A., in research and development laboratory, in a partnership with Faculdade de Engenharia da Universidade do Porto (FEUP). It concerns the study of the twist level and twist direction in yarns and cord aiming to evaluate the load-elongation curves behavior and other properties; yarns of polyester and nylon with the same linear density were chosen. The properties studied were the breaking force, elongation at break, thickness and angles of the cord. Besides it was analyzed the morphology of the fibers in the cord by optical microscope.

The results show that twist affects significantly the cord strength, breaking force and the elongation. A high twist on the cord or yarns is disadvantageous in most cases, unless a high elongation is desired. An asymmetric construction only is advantageous if the twist difference between yarns is close. Cords with the lowest twists levels present highest values of strength at rupture.

Keywords: Polyester, textile reinforcements, yarn, cord, twist, tire.

Resumo

O pneu é responsável por estabelecer o contacto entre a estrada e o veículo. Fornece funções especificas enquanto obedece a um conjunto de críterios de desempenho rigorosos. O pneu é constituido por materiais que vão além de apenas borracha, como são os reforços metálicos e têxteis. Os materias têxteis mais utilizados na indústria têxtil são o nylon, o poliéster, a aramida e o raião. Fibras destes materiais são filamentos, ou fios, interligados contínuos de longo comprimento, e são torcidos para formar uma corda. Este projeto é um estudo que assenta na construção de cordas feitas a partir de materiais têxteis e apresenta uma primeira tentativa no estudo da construção assimétrica.

O projeto decorreu nas instalações da Continental - Indústria Têxtil do Ave, S.A., no laboratório de investigação e desenvolvimento, numa parceria com a Faculdade de Engenharia da Universidade do Porto (FEUP). Neste trabalho é estudado o nível e direção de torção nos fios e na corda, e tem como objectivo estudar o comportamento das curvas força-alongamento assim como outras propriedades; foram escolhidos fios de poliéster e nylon, com a mesma densidade linear. As propriedades estudadas foram força e alongamento à ruptura, espessura e angulos na corda. Além disso, foi analisada a morfologia das fibras na corda recorrendo a um microscópio óptico.

Os resultados obtidos mostram que a torção altera significativamente a resistência da corda, a força de ruptura e o alongamento. Uma torção elevada na corda, ou nos fios, é desvantajoso na maioria dos casos, a não ser que se deseje um alongamento elevado na corda. Uma construção assimétrica apenas é vantajosa se a diferença de torção entre os fios for baixa. Cordas com níveis baixos de torção apresentam os valores de força à ruptura mais elevados.

Palavras-chave: Poliéster, reforços têxteis, fio, corda, torção, pneu.

Declaration

I declare, under honor commitment, that the present work is original and that every non-original contribution was properly referred, by identifying its source.

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Notation and Glossary

TL	twists level	tpm
dtex	dcitex	g/10000 m
σ_{break}	Breaking force	N
$\varepsilon_{\mathrm{break}}$	Percent elongation at break	%
$\varepsilon_{45\ \mathrm{N}}$	Percent elongation at a specific force, 45 N	%

List of acronyms

ASTM	America Society for testing and Materials
C-ITA	Continental - Indústria Têxtil do Ave
FEUP	Faculdade de Engenharia da Universidade do Porto
HMLS	High modulos low shrinkage
LTU	Laboratory Twisting Unit
LDU	Laboratoru Diping Unit
PET	polyester
HMLS	High modulos low shrinkage

1 Introduction

1.1 Project presentation and framework

Tires have a complex structure, they are highly engineered in order to achieve mostly security, service life and ride comfort. Choosing to improve one of its features always means a loss of others performance and it becomes necessary to settle for a compromise between opposing characteristics. Not all tires require the same characteristics since their needs depend mainly on the environment, road conditions in which the vehicles travel and the vehicle top speed and weight.

The evolution of motor vehicles went from a time where tires were not considered to have a significant impact in the performance of a vehicle, to one where cars are capable of reaching high speeds, and are used in diverse conditions. The tires require highly technological solutions in their design, construction and materials to make it resistant to adverse conditions. The materials that constitute the tire, besides rubber, are the textile and steel reinforcement materials.

In 1871, Continental was founded at Hanover and started with the production of buffers for horseshoes and solid tires for carriage. It had its first success with the manufacturing of pneumatic tires for bicycles only a few years later. In the 1970s and 1980s, the company went international and acquired, in addition to tire production, numerous branches of the automobile industry; such as brake, powertrain and chassis systems, as well as components for other vehicle parts. Nowadays and because of the constant investment on research and development, it is one of the largest manufacturers of premium tires for commercial vehicles.

Indústria Têxtil do Ave (ITA), was founded in 1950, and joined the Continental group in 1993.[1] Its core-business is the textile reinforcement materials, such as tire cords and part of its production supplies Continental Mabor S.A; which is responsible for the development of the tire from raw materials. The scheme presented in Figure 1 shows an overview of the tire manufacturing process.

C-ITA develops the cords and transforms them into fabric. The cords manufacturing process consists in giving twist to the fibers/yarns. Afterwards, and depending on the final destination of the cords, they are transformed into a fabric by the weaving process. The final step applied in the cords, individually or to the fabric, is the dipping process; this step improves the adhesion between cords and the rubber compounds.

The textile reinforcements ensure the structure and cohesion among the materials; by giving the tire a better performance at high speeds and a greater endurance to the abrasion. The most common textiles used in the tire industry are nylon, polyester, rayon and aramid.

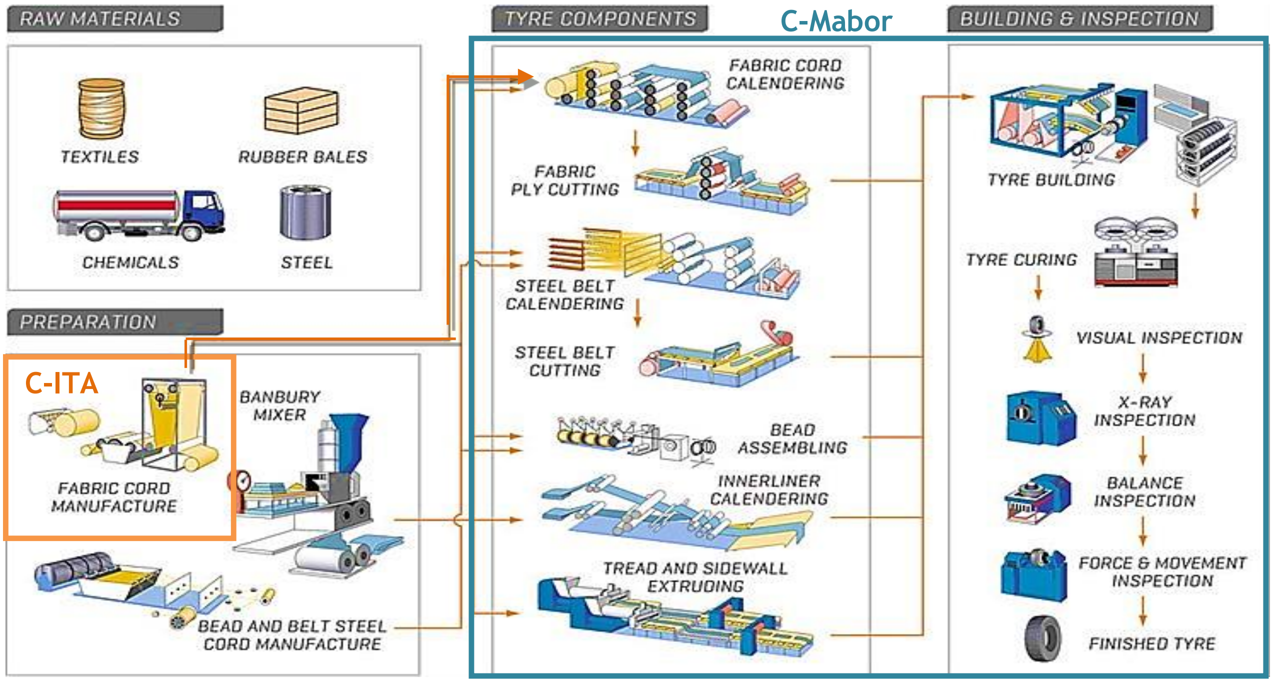


Figure 1 – Schematic representation of the tire manufacturing process.(adapted from[2])

The work development took place at C-ITA through a partnership with FEUP – Faculdade de Engenharia da Universidade do Porto, on the research and development department. It was used some test equipment's and two laboratory units that simulate the twisting and dipping processes, the laboratory twisting unit (LTU) and the laboratory dipping unit (LDU), respectively.

1.2 Project goals

This thesis concerns the development of tire cords with different twist levels and directions (clockwise - S and counter clockwise - Z), which constitutes an asymmetric construction, and studies the influence of those factors on the load-elongation curves. The cords were made with two yarns twisted together; it is possible to do cords with more yarns but that was not covered on this project. The asymmetric cord construction is characterized by having different twist levels simultaneously on yarns and cord. This kind of construction is only possible by using one type of twisting machine, the two-for-one.

1.3 Project Contributions

The importance of this project is establishing the basis for future work in the asymmetric cord construction. It was studied the influence of twist level and twist direction of cords and their response on the load-elongation curves. In the literature it is possible to find studies with different twist levels, but the asymmetric cord construction does not appear to have been subject of study.

Besides the knowledge of load-elongation curves it was possible to obtain a data-base of the created cords. The microscopic analysis contributes for a better comprehension on the direction of the filaments on the cord.

1.4 Thesis Organization

This thesis is organized in 7 chapters and their description is briefly presented next.

Chapter 1. **Introduction:** provides an overview of the tires and Continental background, it is also described the objectives of the project and its main goals.

Chapter 2. **State of the art:** describes the tire and its reinforcement materials, focusing on its properties and cord manufacturing processes.

Chapter 3. **Procedure and technical description:** provides the description of all the experimental work procedures, methodologies, test methods and testing instruments.

Chapter 4. **Results and discussion:** presents the responses of the tests executed, analysis and discussion thereof.

Chapter 5. **Conclusions:** reports the interpretations of the analysis of the work presented.

Chapter 6. **Project assessment:** valuates the work done and the achievement of goals and defines some of the future work.

Chapter 7. **Bibliography** lists all the references used during the project

Annex includes the complementary information.

2 State of Art

2.1 Tire

Since the invention of the wheel, more than 5 000 years ago, the tire has been the subject of several studies and applications, always evolving to meet transport needs for each environment. [3] Because the security of the road transport depends on the quality construction of tires it is necessary a continuous research for new technologies and materials to insure and improve that.

The first tires were bands of leather [4] and then the iron replaced the leather; they were used to cover the wooden wheels of carts and wagons. At the mid 1800's, with the discovery of the rubber and vulcanization process, the construct of tires changed and the solid rubber replaced the iron. The rubber increased the shocks absorption and resistance to cuts and abrasions; on the other hand the tires were heavier and did not provide a smooth ride. [5]

In 1845, Thompson invented and patented the pneumatic tire for bicycle applications. However, it was not given the entitlement to Thompson and, in 1888, Dunlop was credited with a second invention of a bicycle tire, by "realizing rubber could withstand the wear and tear of being a tire while retaining its resilience". [6, 7]

The pneumatic tires started to be used in automobiles in 1895 and did not change much until the steel-belted radial tires started being used, in 1948. The name came from the ply cords that radiate at a 90 degree angle from the wheel rim. Currently, they dominate the passenger tire market. [6] Pneumatic tires are divided by type of construction: radial, diagonal and bias-belted.

The most common tires used in passenger vehicles (90 %) and light trucks are the radial tires. This is because they have easy deflection at load, low heat generation which provides a lower rolling resistance and better high speed performance. However, they have a higher manufacturing cost due to its complexity.[8] The radial tire may have more than 20 components, 15 of which are rubber and the rest are the reinforcement materials; textile and steel cords.

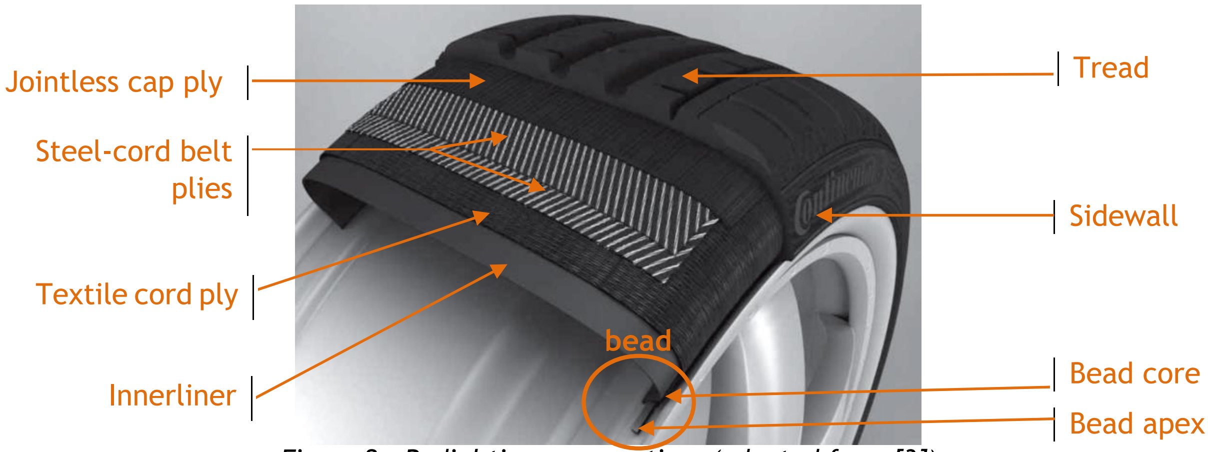


Figure 2 – Radial tire cross section. (adapted from [3])

The Figure 2 shows the different constitution parts of a radial tire from a passenger car. It structure can be divided into 3 parts: the rubber of the external part, the reinforcement parts and the innerliner. The tread and sidewall are the parts of the tire in contact with the road and must provide a good grip or traction for driving, braking and cornering; features that depends on the weather conditions: dry, wet, snow-covered and icy surfaces. The sidewall must protect the tire from abrasion, impact and flex fatigue.

Figure 2, the layers that follow the tread and sidewall are the jointless cap-ply and bead; the cap-ply is composed by textile materials embedded in rubber and lied radially, offering restrict expansion from centrifugal forces during high speed rotation. The bead has 3 parts: the bead reinforcement which configures directional stability and precise steering response, the apex that adds comfort level and the bead core which ensures a perfect fit on the rim. [3]

The steel-cord belt plies will add strength and directional stability because of the two or more belts lied diagonally in the tread region. Then, textile cord ply is lied 90 degrees to the direction of travel and maintains the cord shape and controls internal pressure. Finally, the innermost layer is the innerliner, made of rubber only; it retains the air-filled inner chamber by lowering permeation outwards. [3]

2.2 Reinforcement materials

The tire's reinforcement materials offer structure and cohesion among the rubber and those materials. The rubber compounds consist on natural or synthetic rubber, carbon black, curing agents, cure accelerators, plasticizers, protective agents and other ingredients.[8] The reinforcement materials are the steel and textile cords and offers structure; the textile cords predominate in jointless cap ply and the steel cords on belt and jointless.

2.3 Textile material

The textile cords must yield a durability to the tire against bruise and impact, a support to inertial load, imprison the inflating gas, provide rigidity to accelerating, cornering and braking and provide dimensional stability for uniformity, ride and handling. There are different materials that cords may be done with.

The most common materials used in the tire textile industry are the polyamide 6 and 6.6 (nylon), the polyester, rayon and aramid. Their chronological order of appearance along the history is: cotton in 1910, rayon in 1923, nylon 66 in 1947, polyester in 1962 and aramid in 1974.[9]

Rayon was the first manufactured fiber and its first use was in truck tires bringing an improvement on the carcass performance. Its production for the tire industry hit a peak in 1949 but rayon properties did not follow the development of the automobile vehicles and the nylon replaced it in the late 1950's.[9] Rayon is still used in some run-flat tires as body ply material. It is resistant to heat, it is dimensionally stable at high temperatures and has good handling characteristics, but it is expensive, has environmental manufacturing issues and it is sensitive to moisture.

Nylon fibers are synthetic polymers and provide high strength and abrasion, good elasticity, fatigue resistance and uniformity, as well as resistance to moisture to the tire. With the improvement of roads in developed countries, the use of nylon in tires decreased because it has a poor dimensional stability at high temperatures and for high speed roads the heat resistance properties is valuable. Nylon fibers are still applied on tires of vehicles used in developing countries. Its high energy absorption makes it suitable for poor road surfaces. They are also used in trucks, buses and off-road vehicles to reduce the production cost.[6, 10]

Polyester, polyethylene terephthalate (PET), is a synthetic long chain polymer and was introduced to the marketplace in 1962.[6] The polyester provides a better high speed performance to the tire due to its high modulus; the low elongation prevents the tire growth and deformation with friction/heat. It is dimensionally stable but is not as resistant to heat as nylon or rayon. It has low adhesion and low fatigue resistance. Nowadays, it is the most used fiber worldwide in tires and it is applied on the carcass of radial tires for passenger cars or light trucks.[11]

The aromatic polyamide, aramid fiber, appeared in the 1970's.[9] The main feature of this textile is being two to three times stronger than polyester and nylon. It has a high heat resistance and high stiffness. Those advantages allow applications of aramid in belt as a light weight alternative to steel cord or as a stabilizer material. Their disadvantages are the cost, processing constraints , since it is difficult to cut, the weak adhesion to rubber and low fatigue resistance.[6]

Figure 3 presents a comparison of the typical load-elongation curves for each yarn material.

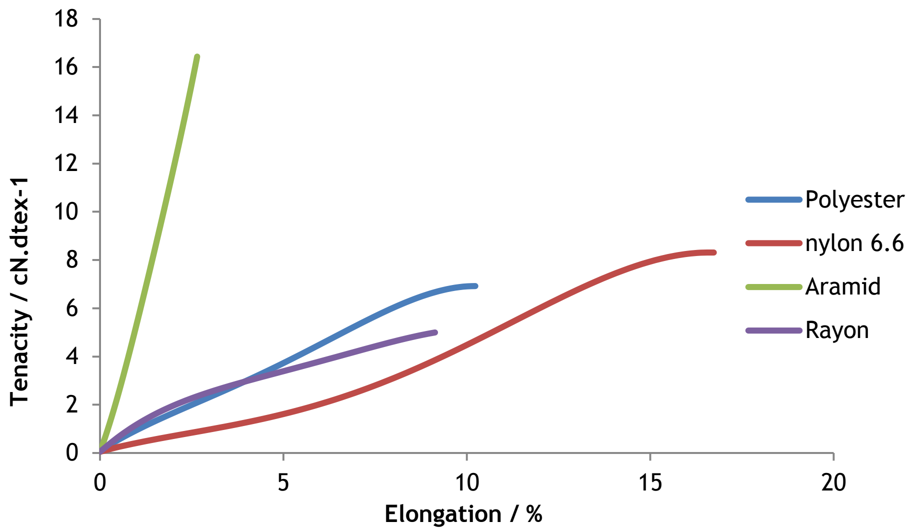


Figure 3 - Typical curves of load-elongation for the different materials.

Table 1 shows some properties of the textile reinforcements mentioned above.

Table 1 - Properties of the textile fibers used in tire industry.[7]

Properties:	Polyester	Nylon 6.6	Rayon	Aramid
Tenacity (cN/Tex)	80	85	50	190
% Elong at break	13	16	6	4
Modulus (cN/Tex)	850	500	800	4000
Shrinkage (% at 150 °C)	2.0	5.0	<0.1	<0.1
Moisture regain (% at RG)	0.5	4.5	13	<2.0
Melting temperature (°C)	250	250	>210	>500
Glass transition temperature (°C)	80	55	-	-
Heat resistance (°C)	180	180	150	250
Approximate relative cost per unit weight (PET=1.00)	1.00	-	1.33	5.00

All fibers mentioned are polymers and they are distinguished by their intrinsic properties, such as its intermolecular interactions and crystal morphology. The PET and nylon fibers have a semi-crystalline, while the rayon and aramid have a paracrystalline structure. The semi-crystalline arrangements have highly ordered domains, or crystalline phase, that coexists with regions containing randomly coiled chains, or amorphous phase. The paracrystalline structures do not consist of two separated crystalline phases but they have an extended chain structure or oriented amorphous structures, Figure 4. [12, 13]

The semi-crystalline structures have moderate strength, moderate modulus, high elongation at break, shrinkage, creep, high flexibility and their properties are a function of the temperature. PET and nylon fibers differ from one another on the quantity of amorphous/crystalline regions.

The nylon has more amorphous regions compared to the polyester. The same material can have different values of crystallinity; this is observed either because of manufacturing procedures or any after treatments.[14]

The paracrystalline fibers have higher strength, no shrinkage, high flexibility and their properties are not a function of the temperature.

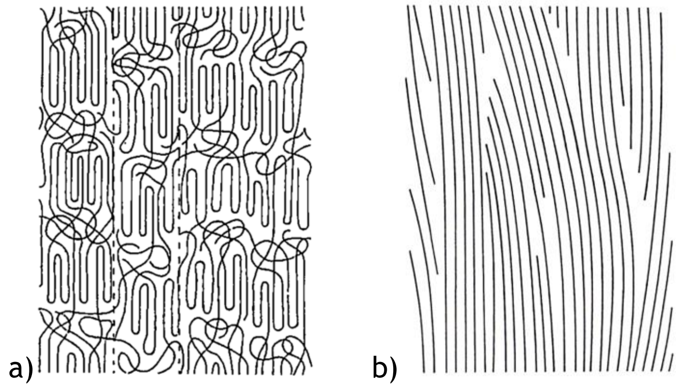


Figure 4 – Representative pictures of the polymer chain orientation: a) semi-crystalline and b) paracrystalline. (adapted from [15])

2.4 Textile nomenclature

The textile industry uses a common vocabulary/nomenclature, and since this work focuses on the construction of cords it is necessary to define the terminology used:

FILLAMENT	Continuous manufactured fiber material with a length of at least 100 times greater than its diameter.
YARN	Generic term for continuous filaments or strand of textile fibers, resulting from the spinning process.
PLY	Yarns twisted before assembling into cords, twisting process.
CORD	Product formed by twisting together two or more plied yarns. It is characterized by the twist level, twist direction and linear density.
DECITEX (DTEX)	A unit to express linear density, corresponds to the weight in grams of 10 000 meters of yarn, filament or fiber.
TWIST LEVEL	Number of turns per unit length of a yarn or cord, usually expressed in twists per meter (tpm). The yarn twist brings the fibers close together and makes them compact, which helps the fibers adhere to one another, increasing yarn strength.
TWIST DIRECTION	Direction of twist in yarns or cord is indicated by the capital letters S and Z. It is designated “S” if the spiral turns clockwise from top to bottom for a vertically held cord and “Z” for a similar counter clockwise turning.

TENSILE STRENGTH	The breaking force required to rupture a cord at a given rate of extension, is expressed in Newton's (N). The tensile strength is calculated by dividing the load at break by the original sample section.
GREIGE CORDS	To apply the cords on the tire it is necessary to dip them in a solution so that they may subsequently adhere to rubber. The greige cords corresponds to the twisted cords before this process.
TENACITY	It is the force per unit linear density.
YOUNG MODULUS, E	Slope of the load elongation curve where load and elongation are linear, expressed in N/%

2.5 Cord

The cord is built up from yarns, the yarns from filaments and filaments from fibers. Figure 5 presents an overview of the manufacturing process of textile reinforcement:

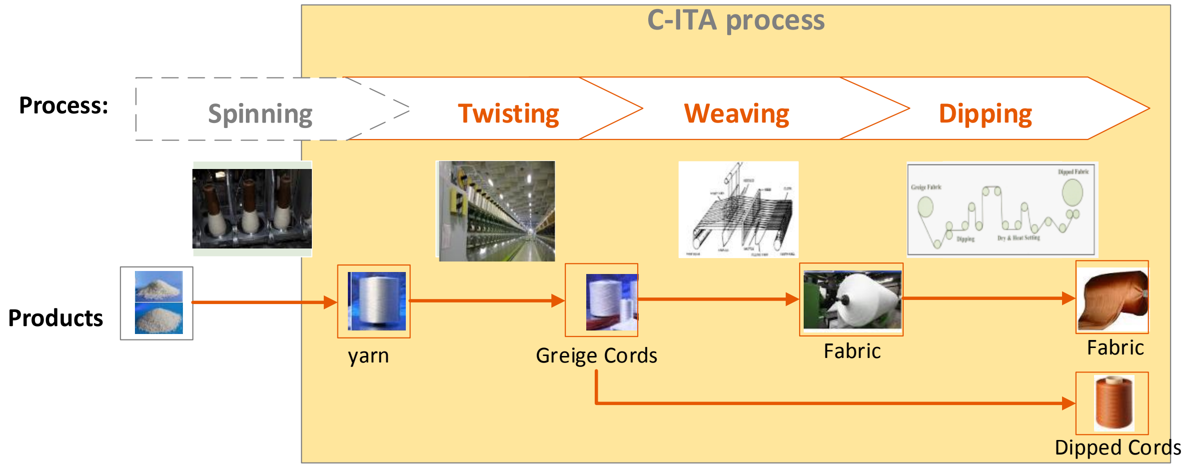


Figure 5 – Textile reinforcement manufacturing process.

The industrial process to make textile reinforcements begins with the spinning. If the fiber is natural the process starts with drawing out the fibers from a mass and twisting them together to form a continuous thread or yarn. In a production of man-made fibers the spinning process begins with the extrusion of a solution to form a fiber and then the twist of the fibers to form a yarn. The most common industrial techniques are the ring spinning, open-end (rotor) spinning, and air-jet spinning. Some of the spinning processes also include cord construction. [16]

Cord construction (greige cord)

The next process is the **twisting process**, at C-ITA the cord production initiates at this point. It consists in twisting two or more yarns to form a cord, or greige cord. The twist process may occur in one or two steps, twisting the cord directly or twisting the yarns first and then the cord. If the cord is obtained with only one step the direct cabling process is used. If the cord is made in two steps the processes used can be the flying spinning, ring spinning or two-for-one twisting, Figure 6.

On the direct cabling method the yarns are twisted around each other in a single operation without introducing twist to the single yarns, and on the two-for-one method it is possible to have a cord with different twists on plies and cord.[16]

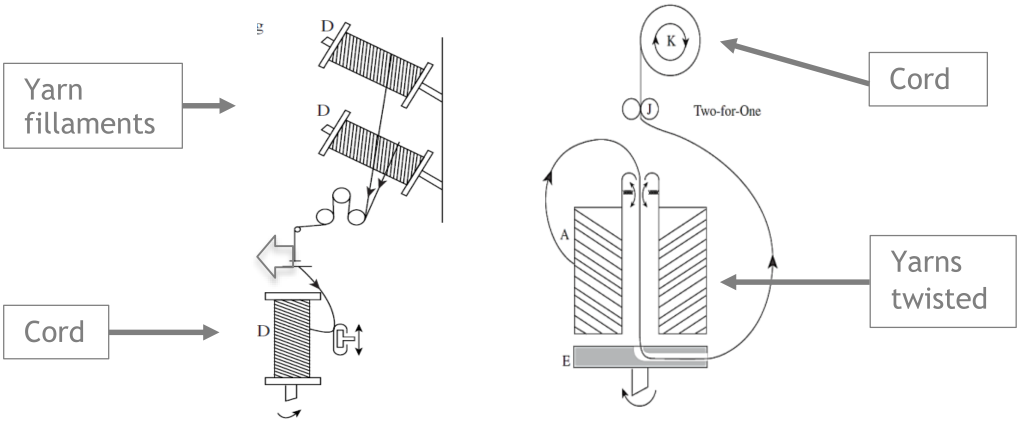


Figure 6 –Twisting processes schematics: (A) ring twisting (B) two-for-one. (adapted from [16])

The purpose of twisting is to give cohesion to the yarns, providing a certain abrasion resistance, fatigue and other types of deterioration associated with tensions, by improving the strength, flexibility and weight. [17]

A cord is characterized by the twist level, twist direction, type of construction and linear density (dtex), Figure 7. The cord construction can be represented, i.e., polyester cord with two plies as: PET dtex1x2. The linear density of the cord is calculated by adding the linear density of each yarn that composes the cord; the contraction factor is not taken into account and it can be considered negligible.

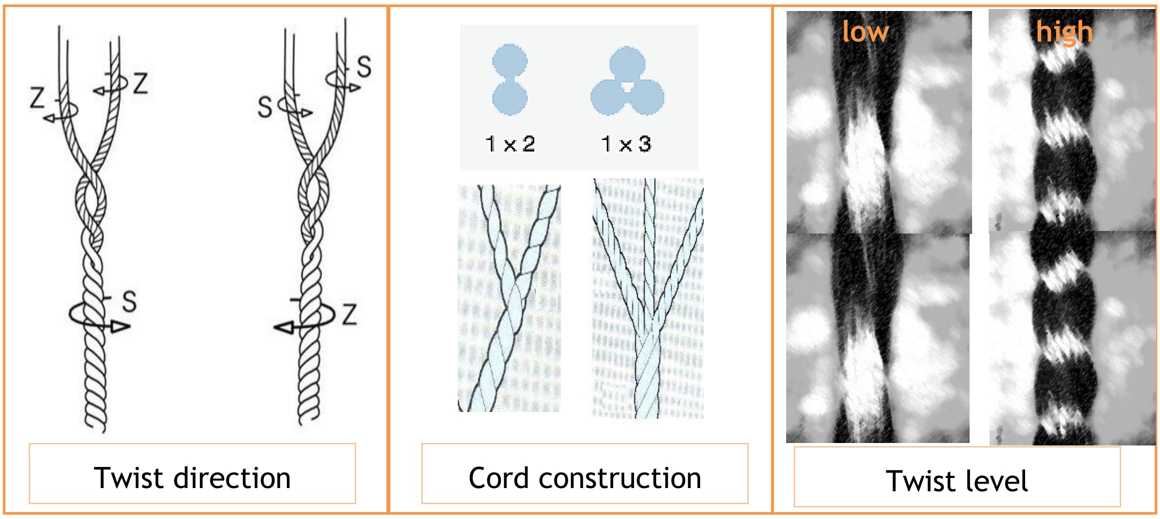
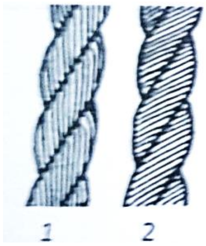


Figure 7 – Representation of the cord twist direction, cord construction and twist level (adapted from [18] and [19])

The two-for-one process was used on the development of the cord of this project. It consists on twisting two or more yarns together forming two or more plies lied parallel and then, in a second step, they are twisted around each other to form the cord.
The cord twist is usually opposite to the yarns twist (twist-against-twist) but the cord construction can be done with the same twist direction for cords and yarn (twist-on-twist) - Figure 8. The cords with twist-on-twist are unstable because the fibers in plies will eventually come to lay on a steeper twist angle, likewise the cord and the yarn will compact to a smaller diameter. [16]



Cord with two plies construction:

1- Twist-against-twist
2- Twist-on-twist

Figure 8 - Representation of two cord with different direction construction (adapted from [17]).

Typically, the yarns are twisted in “Z” direction (clockwise direction) and the cord in “S” direction (counter clockwise) - Figure 7, both with the same amount of twist level – balanced construction. The typical cords have a balanced cord construction. In the method two-for-one, the yarns are twisted initially in order to give shape to the yarns and then to the cord, otherwise by twisting directly the cord the filaments of each ply would bond and the cord would seem as a single ply with double the filaments. The number of twists applied on the yarns or cord is given in turns per meter (tpm).
On the construction two-for-one, the concept of initial and final twist on the yarns is important along this thesis. By applying a certain amount of tpm on the yarns and then the same amount on the cord, but in an opposite direction, the yarns will lose the initial twist applied and they will lie parallel to the yarn axis with no twist. The final twist on yarns is calculated by subtracting the initial yarn(s) twist applied with the twist applied to the cord if they have opposite directions, otherwise the calculation is done by adding
It is possible to make cords with different twists on each yarn and cord, this is an asymmetric construction. An asymmetric cord can be divided into two types: an asymmetric cord with balanced yarns, meaning the cords and yarn have different twist but both yarns have the same twist level; and the asymmetric cords with asymmetric yarns, meaning the cords and yarns can have a different or equal twist level, withal both yarns have different twist levels.
An important factor that highly influences the properties of the final cord, i.e. curve load-elongation, are the filaments and the yarn angles.
Along the study it was considered two angles, as show in Figure 9, the cord angle and the yarn angle. The cord angle is the angle between the yarn axis and the cord axis and corresponds to

the way that the yarn or ply lies on the cord. A cord with a high twist will have a higher angle. The same is applied for the yarn angles, which corresponds to the angle between the filaments and the cord axis, related to the way the filaments are fitted on the plies.

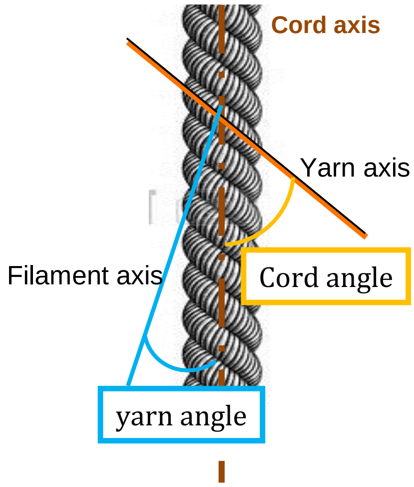


Figure 9 – Cord angles considered.

The twists applied and consequently the angle on the cord has a high influence on the load-elongation curves. The load-elongation curves, as show in Figure 3, are obtained by performing the tensile test. This test outputs values of breaking force, elongation, elongation at break and force at a specific elongation (FASE). The FASE is the force necessary to stretch the cord to a specific percent of elongation. The way the materials respond to the force applied characterize the material on the nature of the material, temperature, time and processing conditions of the cord. Metallic and polymeric materials response obey to Hook's law, which corresponds to the linear part of the of load-elongation curve, also known as elastic behavior.[20]

The step that follows on the production process of the tire textile reinforcements, or greige cords, is the **weaving process**. The conversion of the cord into fabric is accomplished on the weaving machine by interlacing the cord on the longitudinal direction (warp) with yarns of cotton on the transverse direction (weft). The spaces between the cords are denominated inter-yarn gaps.

The final process at C-ITA is the **dipping process**, and consists in emerging the fabric, or the cord, into a solution of Resorcinol, Formaldehyde and Latex (RFL) in a sequence of heat and stretch. Each cord material has a specific solution of impregnation and specific conditions of heat and stretch. This last step offers dimensional stability to the cord and the final product is an impregnated fabric or cord.

3 Procedure and technical description

3.1 Operating Conditions

The effect of asymmetric construction has not been studied before and this thesis provides the basis of the cord properties for future works. The polyester, or PET, was the material chosen to start the project since it is the most used textile material in the tire industry. The poliamide 6.6, or nylon 6.6, was also, used in some additional experiments. The decitex, dtex, of the yarn materials was fixed in 1440 for PET and 1400 for nylon.

The cords were generated in a laboratory twisting unit (LTU) by twisting two yarns in a two-ply cord construction - construction x1x2, using the method two-for-one. This method allows different twists on each yarn and different twists on the cords.

For this work it is important to know the initial twist and the twist of the yarns on the cord, because it influences the positioning of the filaments on the cord and consequently the angle witch inter affects the physical properties. The resulting/final twist on yarn(s) is calculated by subtracting the initial yarn twist applied to the twist applied to the cord if they have opposite directions; otherwise the calculation is made by adding. In example, a construction with (ply tpm direction, ply tpm direction, cord tpm direction), (150 Z, 590 Z, 370 S) results in the following final twists and direction (220 S, 220 Z, 370 S). From the example and since the resulting twist of the first yarn is 220, it has the same direction of the cord and it is represented as 220 S. The construction can be asymmetric with balanced yarns or have asymmetric yarns and cord.

This project has three process parameters of study: the twist level of cords and yarns, the twist direction of the yarns and the material of the yarns.

The project spanned a short period of time which restricted the number of cords that were dipped with normal production conditions of heat and stretch, on a small-scale dipping machine or laboratory dipping unit (LDU). The choice about the cord to impregnate was made by taking in consideration the level of construction complexity.

3.2 Design of experiments

To start the project it was necessary to define the method design of experiments. This method is a specific set of experiments defined by a matrix composed by the different level combinations of the variables in study. [21]

In this work, it is essential to understand the response for each parameter on the materials final properties, and the design of experiments - full factorial design - was chosen as a starting point because it considers all possible combinations between the parameter twist levels. The number of factors of the experimental design was 3: cord twist, and both yarns twist levels.

The number of trials was reduced by the condition that both yarns have the same twist level and by some combinations that were considered insignificant; for those reasons the number of trials was reduced from 27 to 15.

The cord twist factor has 3 levels: low (150), medium (370) and high (500). The yarn twist factor has some more in-between values between low and medium and between medium and high; the twist direction for the cord and yarns were fixed in the S-direction and Z-direction, respectively.

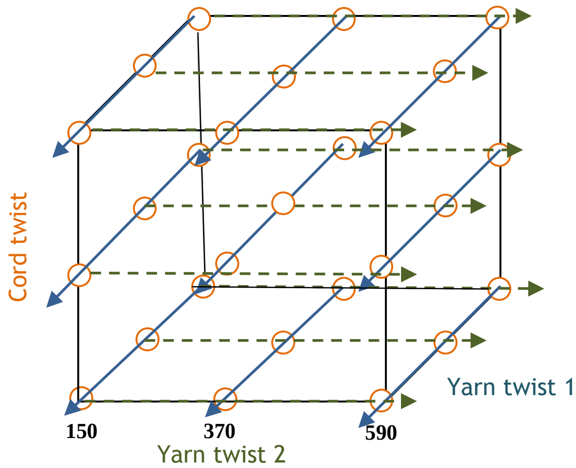


Figure 10 – Scheme of the design of experiments with the variables in study.

On the study of twist direction, the material and twist level were fixed, and only the direction of one or both yarns was changed.

For the nylon study, cords were created with a balanced construction and for the asymmetric construction the cords created have a medium twist level (370 tpm).

The values of the properties of each trial result from a mean obtained of 3 samples, and for each sample a mean of 7 test runs was performed in order to validate the results. This follows a recommended procedure by C-ITA. [22]

3.3 Twisting procedure - Laboratory twisting unit

Figure 11 presents images of the laboratory twisting unit (LTU) where the greige cords were performed. As mentioned before, it is a two-for-one twisting machine:

Figure 11 - Picture of the Laboratory Twisting Unit, at C-ITA.

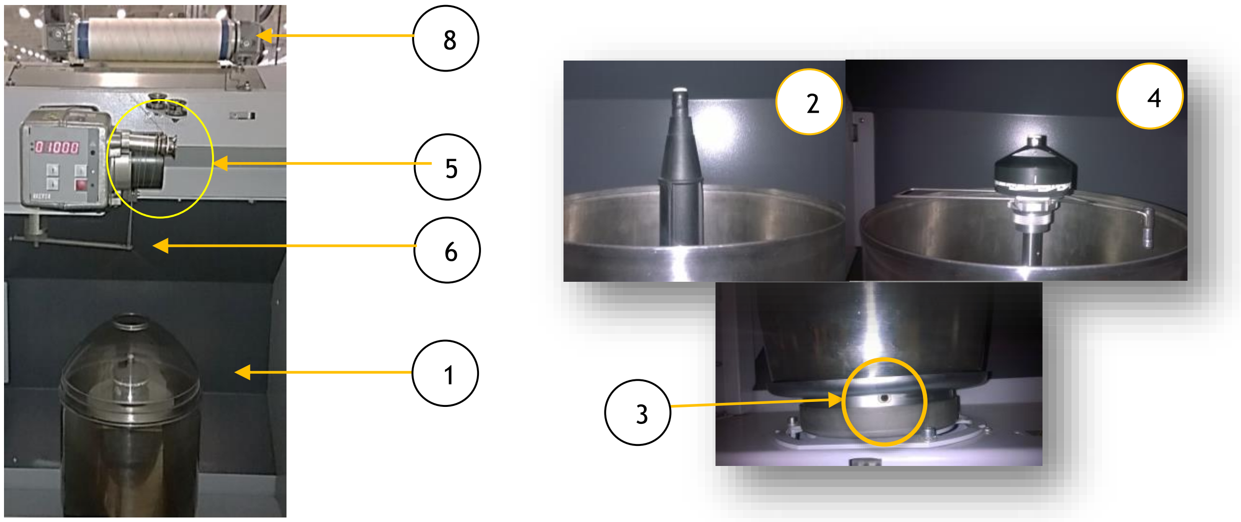


Figure 12 – Individual devices of the LTU.

The laboratory twisting unit (LTU) is composed by different parts and devices, as presented in Figure 11 and Figure 12, and it works with the following principle: The yarn bobbins are introduced in the spindle pot (1) and the yarn is guided to a spindle break (2) and a motor spindle (3), where the yarn rotates around the spindle pot forming a balloon and the cord/yarn gains twist. The spindle break (2) or flyer (4) controls the yarn tension between the motor spindle and the outer yarn delivery system (5), and the arm (6) controls the thread balloon - distance to the spindle pot. The thread is wrapped in the winder roller (7). For each cord construction the arm and the spindle break must be controlled manually.

The computer interface (8) allows to choose the computer program where the parameters can be defined, such as yarn/cord twist level, yarn count, twist direction and spindle speed. The variables of the cord construction are the twist level, twist direction, twisting speed and spindle break.

3.4 Testing procedure

To characterize the properties of the cords performed it was necessary to test the materials. The tests performed are described in the subparagraphs that follows and they provide the properties such as twist level, yarn modulus, force at specific elongation (FASE), breaking force, elongation at break, shrinkage, thickness and some other. The tests were performed according to standard test methods for tire cords, with the exception of the microscopic analyses, and are presented below:

a) *Twist tester* - This equipment allows the confirmation of the twist applied on the yarns and cord. The twists, in turns per meter (tpm) of the greige cords and yarns were measured using a Zweigle twist tester (Germany), according to ASTM D885M. The tolerance allowed was 15 tpm and the pretension applied to the sample is 5 % of the cord decitex.

b) *Tensile Tests* - In the tensile tests performed, the cord is subjected to an axial load until it breaks and this allows obtaining the information about the force necessary to break the cord and at the same time register its elongation. The tensile tests were performed by using a Zwing Roel tester, with cross head speed of 300 mm/min and gauge length of 250 mm according to ASTM D885M. With a pretension of 0.05 dtex. Averages of 7 test runs were done for each sample, and an average of 3 bobbins were done for each cord type.

c) *Gauge tester* - In this test, 4 cords were placed in parallel and the value measured results from an average of the diameter/thickness. A Dial Gage Stand was used, according to ASTM D885M. An average of 4 tests was performed.

d) *Shrinkage and Shrink Force* - Thermal Shrinkage is the amount of shrinkage of the cord while subjected to heat for an established time frame. The tests were performed using a Lensing instrument shrinkage tester at 180 °C for 2 min. The pretension used for the thermal and force shrinkages measurements was 1 % cord dtex. According to ASTM D885M. An average of 5 test runs were done for each type of cord chosen.

e) *Optical Microscopic Studies* - To observe the filaments position on the cords it was used an optical microscope. The equipment is a laboratory microscope Zeiss Model, lenses Zeiss Epiplan-Neofluar for 5x, 10x and 20x magnifications.

A freeware image analysis program, the *Image J*, was used to have some representative results of the angles of the filaments in the yarns and angles of the yarn on the cord.

4 Results and discussion

Aiming to study the physical properties of cords with an asymmetric construction, especially the behavior of load-elongation curves, trials were performed for the twist level, twist direction and material parameters. In this work only it were performed cords with the polyester and nylon, working time did not allow make more experiments or with other. The linear density of nylon and polyester yarns chosen was 1400 and 1440 dtex, respectively.

The tensile tests performed provided the force and elongation curves. This is a destructive test where a force is applied to the cords until they finally break. The curves for each trial are a result of a mean obtained from 3 samples, and for each sample a mean of 7 test runs was performed in order to validate the results.

4.1 Twist level study - Polyester

Because the cord is composed with two yarns, initially only one yarn was tested individually, and afterwards two yarns were lied parallel with no torsion applied to understand the effect of the twist level. Figure 13 shows load-elongation curves for the trials done with a single yarn (orange) or two yarns lied parallel (purple) and two yarns lied parallel with 150 tpm (blue). It is observed for both yarns tested that the elongation depends only on the nature of the molecular structure of the material because the single yarn and the two yarn without twist present the same value of elongation. Comparing the yarns without twist, it is observed that the breaking force doubles because the cross section area of the cord doubles too and the tensile strength decreases proportionally.

As expected, the experimental results show, that the tensile strength of the yarns improve by applying a small amount of twist. The interaction filament-filament partially balances the breaks of filaments and it results in significantly higher bundle strength. [23]

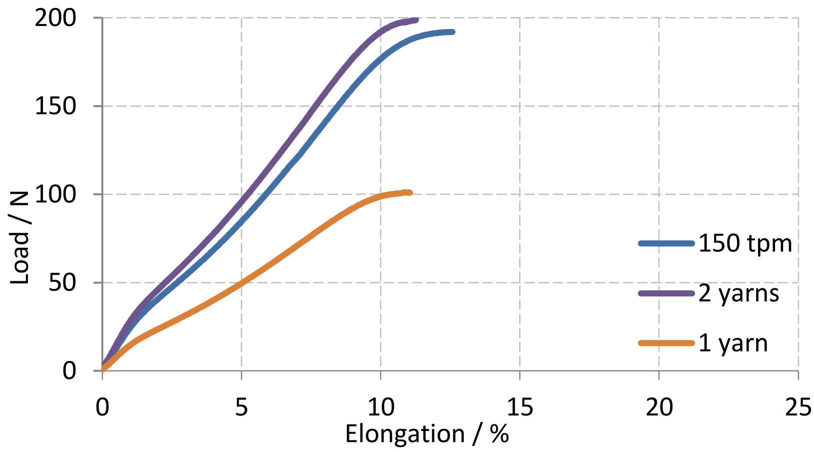


Figure 13 - Curves load-elongation to yarns without twist and for two yarns with 150 tpm.

The curves force-elongation presents two distinctive regions, the elastic region and plastic region. As shows the Figure 13 for the curve with two yarns, the elastic region is the initial linear region between 0 and 25 N and until 2 % elongation and the plastic region correspond to the second part of the curve. The points that characterize polyester curves at level production are the breaking force, elongation at 45 N and elongation at break.
The trials, presented in the following subsections, have the typical direction cord constructions; Z direction to the yarns and S direction to the cord.

4.1.1 Balanced cord construction

Figure 14 shows optical microscopic images of two ply polyester greige cords with three different twist levels with balanced construction. It is possible to observe the filament direction on the yarns. To form the cord the yarns lose their initial twist and at the end the final twist is 0 tpm; and it was expected they would lay parallel to the cord axis, however the cord twist influences the positioning of the filaments and the filaments do not lay perfectly with the cord axis direction. The direction of the plies is determined by the twist direction of the cord.
Figure 14 also shows that with the increase of the number of turns per meter (tpm) the amount of yarn on the cord increases too, this effect leads to a higher thickness/diameter.

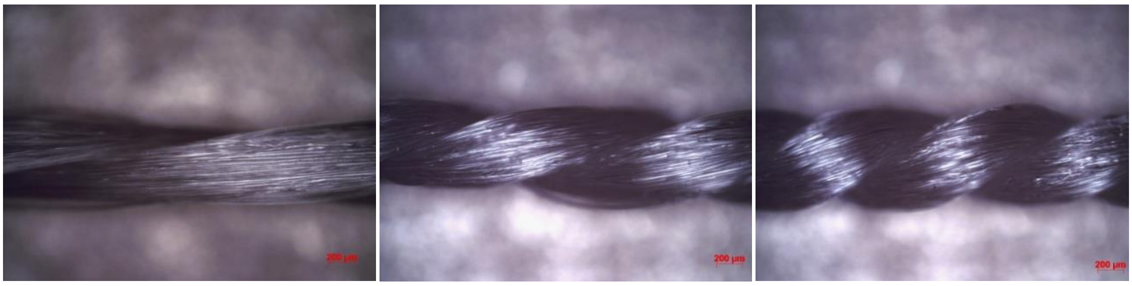


Figure 14 – Microscopic images of polyester cords with different twist levels (a) low (150) tpm (b) medium (370) tpm (c) high (500) tpm. (magnification 5x)

On the tensile tests performed, the cord was subjected to an axial load until it breaks, the test gives the information about the force necessary to break the cord and at the same time registers the elongation. With the increase of twist level on the cord the elongation increases too and the breaking force decreases. The angle decreases the resistant forces - Figure 15. [24]

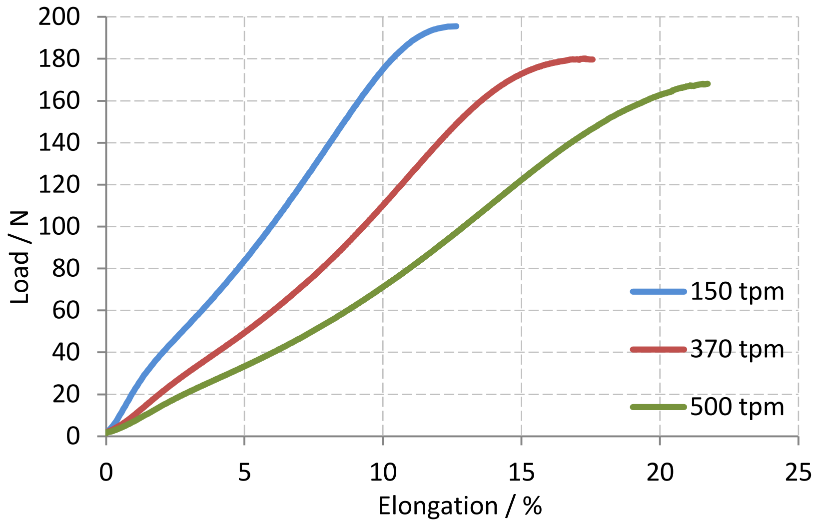


Figure 15 - Variation of cord twist level on load-elongation curves.

When the cord is being stretched the yarns deformation includes the tensile, bending and torsional deformations between the filaments and between yarns, and those factors influences the cord resistance. [25] The resistance forces acting on the cord are a result from the intrinsic properties of the material, from the different directions of the yarns and interfiber bonds. A cord with high twist will offer a lower resistance to the load because the interfiber bonds are high.

Table 1 – Data values obtained for the cords with balanced construction

Cord twist (tpm)	Breaking Force (N)	Elongation at Break (%)	Thickness (mm) ± 0.001	Angles (°)	
				Cord angle	yarn angle
156 ± 4	196 ± 1	12.7 ± 0.1	0.542	9.4	5.0
370 ± 8	180 ± 1	17.0 ± 0.3	0.676	20.0	9.0
502 ± 8	164 ± 4	21.2 ± 0.9	0.693	25.0	20.0

Table 1 contains experimental data of the real cord twist, the breaking force, the elongation at break, the thickness and the angles measured, for the trials performed with balanced construction. The results show that with the increase of the twist level; the elongation at break, the thickness and the angles increases too.

4.1.2 Unbalanced cords

This section presents the study of unbalanced cords and where the results are presented by subdivisions of cord twist levels, which means the cord twist level has with the same value and the yarns twist are changed, one or both yarns . As mentioned before, the twist levels of cords in study were set on low (150), medium (370) and high (500) tpm.

Cord twist: Low Level (150 tpm)

The following scheme shows the face of the combinations used in this section from the cube of the factorial. The points represent the experimental combinations for the factorial design.

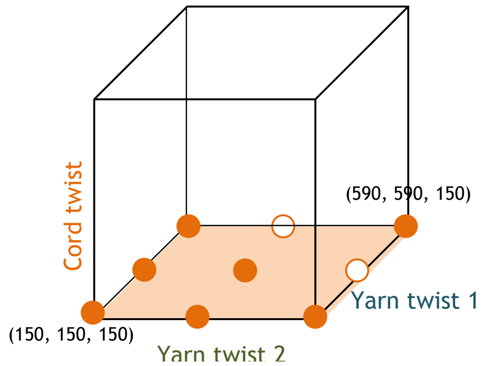


Figure 16 – Representation of the trials combinations performed for cords with 150 tpm for the variables yarns twist.

All the cords have the same twist level, 150 tpm, and it was done combinations of the factors yarn twist. If both plies have the same the construction of the yarns is balanced but if both yarns have different twist the construction of the yarns is asymmetric.

As mentioned before, the cord is made in two steps, first the yarns are twisted and next the cord is twisted and the yarns lose the initial twist applied. Example, for the purple curve for the Figure 17 (a) the construction as (ply, ply, cord), it is (590 Z, 590 Z, 0) initially for yarn construction and at the end, for the cord construction, it is (440 Z, 440 Z, 150 S). The same, for the purple curve Figure 17 (b), initially the construction is (150 Z, 590 Z, 0) and at the end the cord is represented as (0, 440 Z, 150 S). Table 2 presents the corresponding values between the initial and final twist on yarns, notice that the yarns and cord have opposite direction.

Table 2 - Correspondence between initial twist and the final twist applied to the yarns, for the cords with 150 tpm.

Cord twist (tpm)	Initial yarn twist (tpm)	Final yarn twist (tpm)
	150 Z	0
	260 Z	110 Z
150 S	370 Z	220 Z
	480 Z	330 Z
	590 Z	440 Z

Legend of curves Load-elongation

Figure 17 (a) and (b) presents the load-elongation curves for cords with balanced and asymmetric yarn construction, respectively:

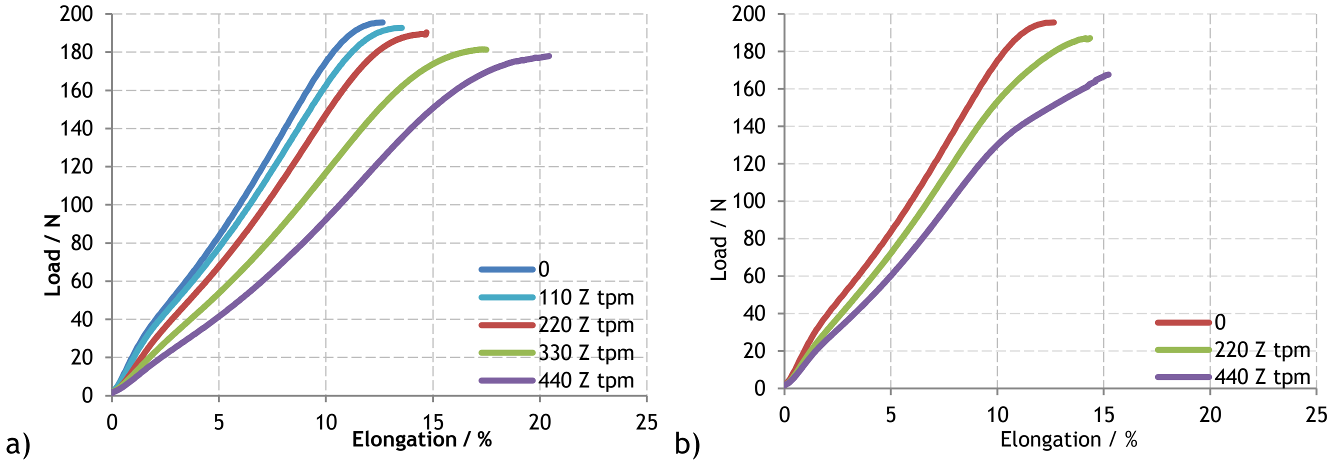


Figure 17 - Load-elongation curves for cords with 150 tpm: a) same twist level for both plies; b) one yarn with 0 tpm and the other with respectively 0, 220 and 440 tpm.

For the cord with low twist, the increase of yarn twist increases the elongation at break and it is observed a significant difference on the elastic region (Load [0-20] N). This results from the increase of filaments angle relative to axis of the cord, this obliquity of the filaments allows a higher elongation.

It is observed in Figure 17 (b) that when only one ply has a high twist level, it presents a different behavior at break and a lower value of tensile strength. The difference between the plies leads to the break of the yarn with the lower twist in first. It is notorious the moment of breaking of the first yarn (10 % Elongation and 125 N load); after this point the curve exhibit a linear behavior.

The distance between the curves of load-elongation of the cords with 330 Z and 440 Z tpm, Figure 17, from the other curves of load-elongation indicates that a high degree of twist on yarns decrease the tensile strength. Those two cords have higher yarn angles, inter-fiber interaction and the lateral compression over filaments compared to the other cords. Figure 18 shows the damages caused on filaments by the high initial twist applied initially on the fibers, as presented at Table 2. Nylon and polyester fibers properties are critically affected with the high twist.[26]

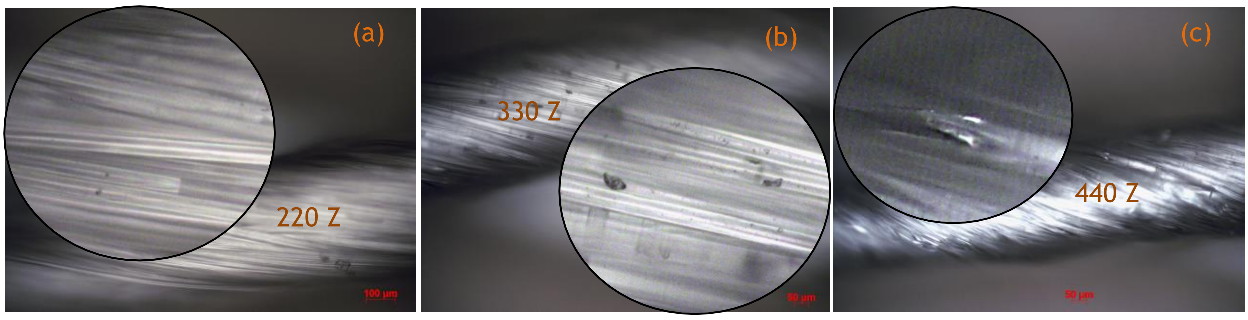


Figure 18 - Comparison of microscopic images (10x magnifications) of cords: (a) without, (b) and (c) with damages caused by initial twist on yarns.

Table 3 resumes some values of the experimental data and is organized by a descending order of the breaking force values and ascending order of twists on yarns. One can conclude there is no significant difference between the values of breaking force and elongation at break for medium twist trials, 220 Z, by varying the twist on one or two yarns. The same does not happen for the trials with high twist, 440 Z, because on the cord with asymmetric construction the difference of the twists between the yarns is high and one of the yarns breaks first.

Table 3 - Comparison between the values that characterize the cords with 150 tpm, for cords with same twist level for both plies and one yarn with 0 tpm and the other with respectively 0, 220 and 440 Z tpm.

Final Twist / tpm						
Cord	Yarn 1	Yarn 2	**Breaking Force / N**	**Elongation at 45 N / %**	**Elongation at break / %**	**Thickness / mm**
150 S	0	0	196 ± 1	2.4 ± 0.05	12.7 ± 0.1	0.542
	110 Z	110 Z	192 ± 1	3.05 ± 0.08	14.0 ± 0.3	0.676
	220 Z	220 Z	189 ± 1	2.62 ± 0.02	13.5 ± 0.2	0.706
	220 Z	0	186 ± 1	3.05 ± 0.08	14.0 ± 0.3	0.638
	330 Z	330 Z	181 ± 2	4.2 ± 0.1	17.2 ± 0.4	0.702
	440 Z	440 Z	176 ± 2	5.4 ± 0.1	19.3 ± 0.6	0.826
	440 Z	0	165 ± 6	3.7 ± 0.1	15.0 ± 0.8	0.827

Figure 19 presents the relation between the angles and twist level for the cord with balanced construction.

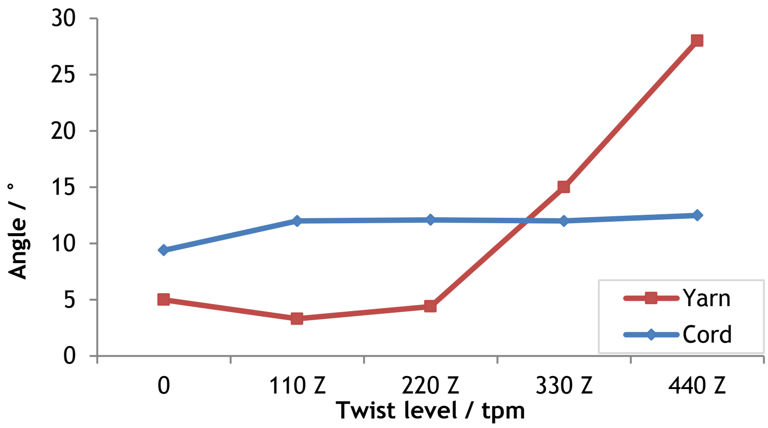


Figure 19 - Relationship between angle values of the cord and yarn with twist level, for cords with 150 tpm and same twist level for both plies. (lines were added for readability)

Figure 20 presents the relation between the yarn angle and breaking force for the cord with balanced construction.

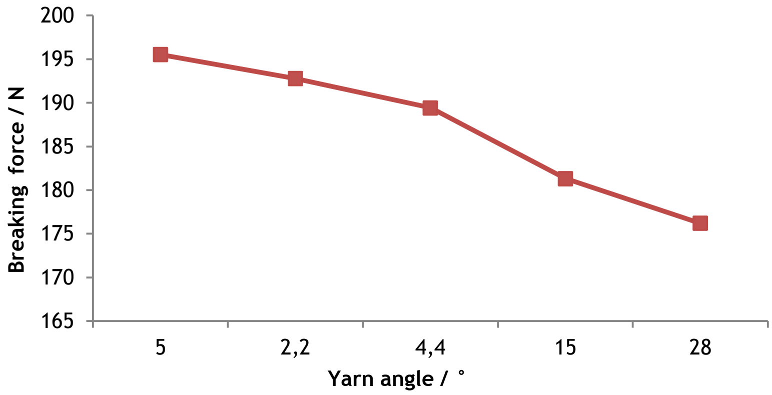


Figure 20 - Relationship between breaking force and angle values of the yarns, for cords with 150 tpm and same twist level for both plies. (lines were added for readability).

It was expected the same angle value for the cord for all experiments because all cords have the same twist, however, as Figure 21 illustrates, the yarn twist modify slightly the cord angle. The relation between the yarn angle and breaking force is linear and inversely proportional; with the increase of the twist angle the breaking force decreases.

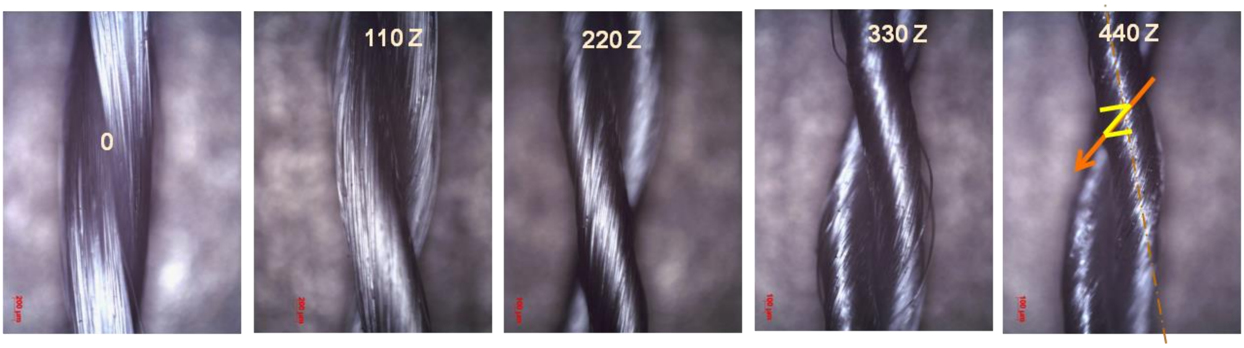


Figure 21 - Microscopic images of each cord with low twist level and similar twist level on both plies. (magnification 5x)

Because the angle measurement method is not accurate, is only possible to affirm that the yarn angle increases significantly for the trials with high twist. A cause for this fact is that the damage caused on fibers may block the un-twist of the yarns in the cord construction.

Not knowing the yarn twist direction it is possible to obtain the direction easily by drawing a line on the direction of filaments and two lines perpendicular to the axis yarn, the letter formed by them, S or Z, corresponds to the twist direction, as represented Figure 21 on last cord. For the direction of the cord the process is the same, but it is draw a line in the direction of the wire, yarn axis and two lines perpendicular to cord axis.

In Annex 1 is possible to observe the microscopic images from the cords made for the cords with low twist. The construction with the asymmetric yarn construction show that the yarn with the higher twist turns through the one with lower twist and is noticeable the difference between the angles of the yarns.

Cord twist: Medium Level

The cords with medium twist level are the most common used in the production. The Figure 22 shows the representation of combinations for experiments performed, the points represent the combinations from the factorial design but some more experiments were done. The points that are not filled mean that those combinations were not done.

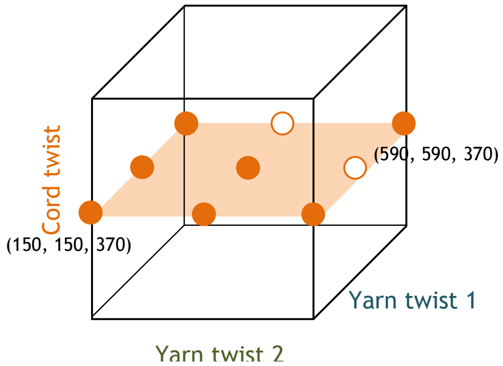


Figure 22 – Representation of the trials combinations performed for cords with 150 tpm for the variables yarns twist.

Figure 23 illustrates the load-elongation curves obtained for the cords with balanced and asymmetric yarn construction and with medium cord twist, 370 tpm. The legends of the figure show the final twists on the yarns, the correspondence between the initial twist level and final twist level is presented in Annex 2.

Initially the trials performed were low, medium and high twist level on yarns, Figure 23. The curves do not present the behavior expected, which would be an equal distance between the curves.

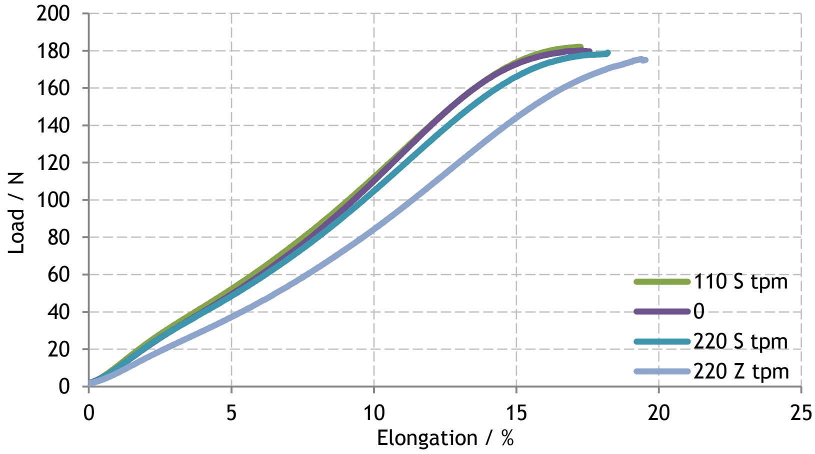


Figure 23 – Load-elongation curves for cords with 370 tpm and both plies with 0, 110 and 220 Z tpm.

To study in detail the effect of the yarn twist on the cord additional experiments with in-between values of twist level were performed and are represented in Table 4.

Table 4 - Comparison between the values that characterize the cords with 370 tpm, for cords with same twist level for both plies and one yarn with 0 tpm and the other with 110 and 220 Z and S tpm (grey coloration).

Final Twist / tpm						
Cord	Yarn 1	Yarn 2	Breaking Force / N	Elongation at 45 N / %	Elongation at break / %	Thickness / mm
	220 Z	220 Z	174 ± 3	6.0 ± 0.1	19.2 ± 0.7	0.738
opposite direction	220 Z	0	167 ± 4	5.7 ± 0.1	19.6 ± 0.9	0.743
	110 Z	110 Z	179 ± 1	5.2 ± 0.1	18.7 ± 0.4	0.721
	110 Z	0	179 ± 2	4.9 ± 0.1	18.3 ± 0.4	0.716
370 S	70 Z	70 Z	181 ± 2	4.9 ± 0.1	17.6 ± 0.3	0.704
	0	0	180 ± 1	4.6 ± 0.1	17.0 ± 0.3	0.676
	70 S	70 S	184 ± 1	4.3 ± 0.1	16.7 ± 0.3	0.636
	110 S	0	181 ± 2	4.4 ± 0.1	17.0 ± 0.4	0.686
	110 S	110 S	182 ± 1	4.3 ± 0.1	17.4 ± 0.3	0.633
	220 S	0	166 ± 7	5.0 ± 0.1	17.4 ± ± 0.8	0.767
	220 S	220 S	178 ± 1	4.6 ± 0.1	17.8 ± 0.4	0.622

The range of values observed for the parameters breaking force, elongation at break and diameter is lower compared to experimental data of the cords with low twist (previous subchapter), resulting from the same proximity between the curves with the highest and lower values.

The curves of the trials 110 S and 0 tpm and of the trials 70 Z and 220 S tpm present a match in pair between both yarns with only a negligible difference on the values of the parameters that characterize the curve, Table 4. Some of the curves are indistinct as therefore as only presented at Annex 2.

For medium cord twist, with the increase of yarn twist the elongation does not increase proportionally due to the final twist level. Therefore the value distribution of breaking force and elongation at break in order to twist level presents a quadratic trend from 220 Z until 0 and other from 0 until 220 S:

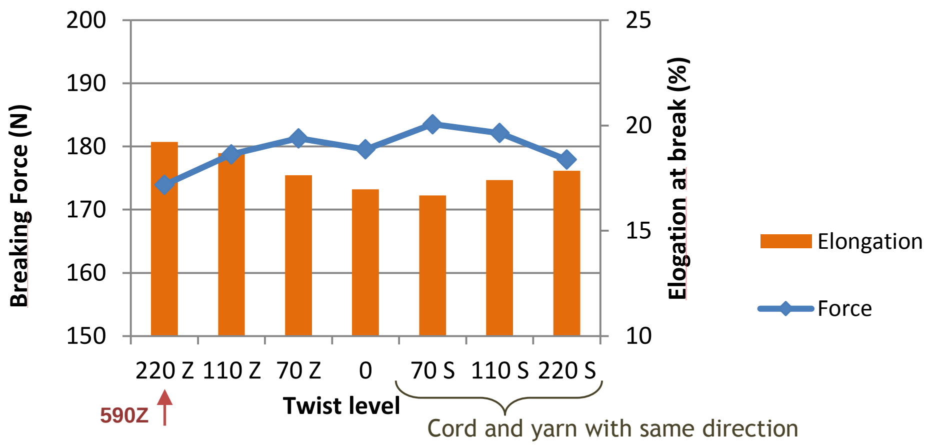


Figure 24 - Breaking force and elongation at break vs yarn twist level, for cords with 370 tpm and balanced yarns.

The yarns and the cord with opposite directions have the higher values for elongation at break compared to the ones with the same direction, Figure 24, because the yarns are unbundled allowing the extra elongation. The force at break is smaller since the filaments are more lined up vertically, Figure 25.

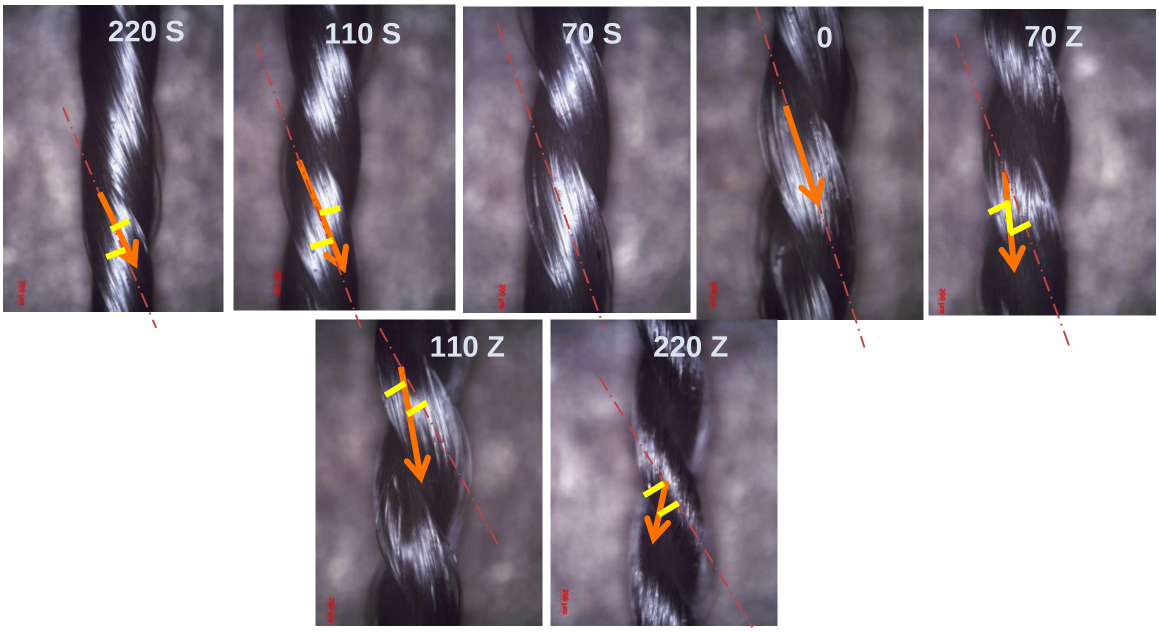


Figure 25 - Microscopic images of each cord with medium twist level and balanced yarns. (Magnification 5x)

The microscopic images illustrates the differences between the cords; in the first three cords the yarns and the cord have the same direction and the initial twist applied is lower compared to the last three cords, where the yarns and cord have opposite direction. One can conclude that the cord shape is defined by the initial twist; cord with high twist, 220 Z, has the yarns unbundled and stiffer compared to the cord formed with the lower twist level, 220 S.

In addition, it is represented in Figure 25 the direction of the filaments on the cord, the Z direction is clearly distinguished unlike the S direction.

When the construction is asymmetric, the values and the behavior of the curves are similar to balanced yarns, Figure 26; the curve with the yarn twist of 110 S and 0 is similar. Also the curves are similar for the trials 110 Z and 220 S but only until round 12 % of elongation, after that point the difference of yarn twists is significant and the yarn with lower twist breaks first.

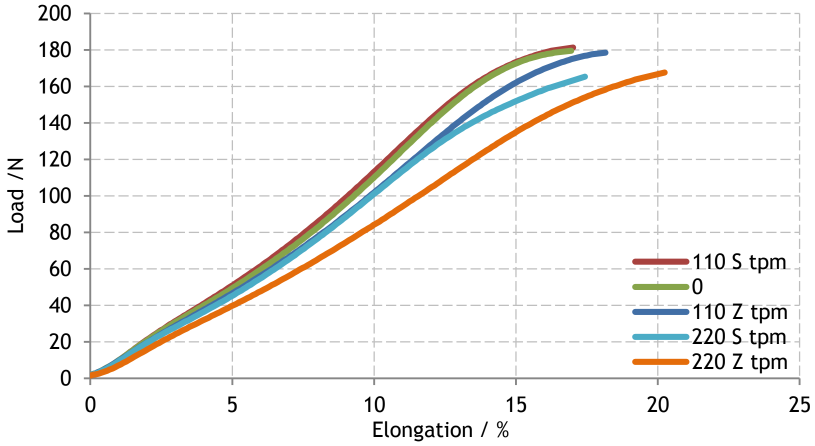


Figure 26 – Curves Load-elongation of cords with medium twist level and asymmetric yarn construction.

Cord twist: High Level

The cords with high twist, 500 tpm, complete the study of twist level. As was done for the previous experiments, the cord twist was kept constant and it was changed the yarn twist in 5 levels, low, in-between, medium, in-between and high.

As mentioned before, the calculation method of the yarn twist is the same and it is presented in Table 5.

Table 5 - Correspondence between initial twist and the final twist applied to the yarns, for the cords with 500 tpm.

Cord twist (tpm)	Initial yarn twist (tpm)	Final yarn twist (tpm)
150 S	150 Z	350 S
	260 Z	240 S
	370 Z	130 S
	480 Z	20 S
	590 Z	0

Legend of curves Load-elongation

Figure 27 presents load-elongation curves for cords with 500 tpm. The values of the legends appear ordered by the reading order of the curves from left to right.

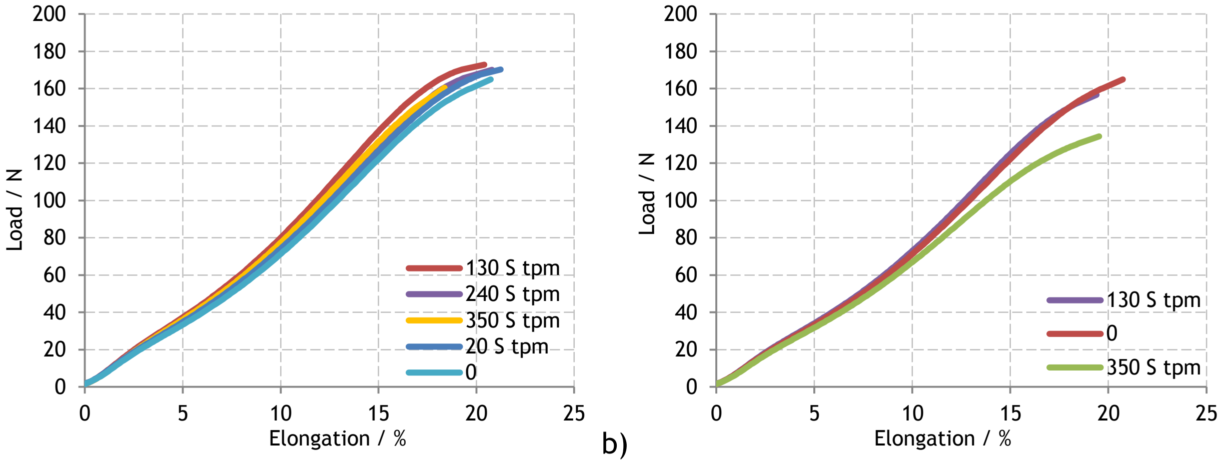


Figure 27 - Load-elongation curves for cords with 500 tpm: a) same twist level for both plies; b) one yarn with 0 tpm and the other with respectively 0, 130 and 350 tpm.

As the Figure 27 a) shows, for a cord with high twist level, the elastic region does not change with the increase of twist level, the cord angle is the higher and the effect of yarn angle it is low.

A cord construction with a high twist on the yarns makes the cord stiffer. The high angle on the cord increase the resistance forces leading to high values of elongation and low values of load. The final construction makes that the yarns and cord will end up with the same twist direction. The experiment with 350 S, Figure 27 a), presents lower values of elongation at break and breaking force which means a fragile cord. This cord was made from yarns with the lower twist and resulted in a cord with both yarns attached and resemble as a single ply, as can be observed in the Figure 27.

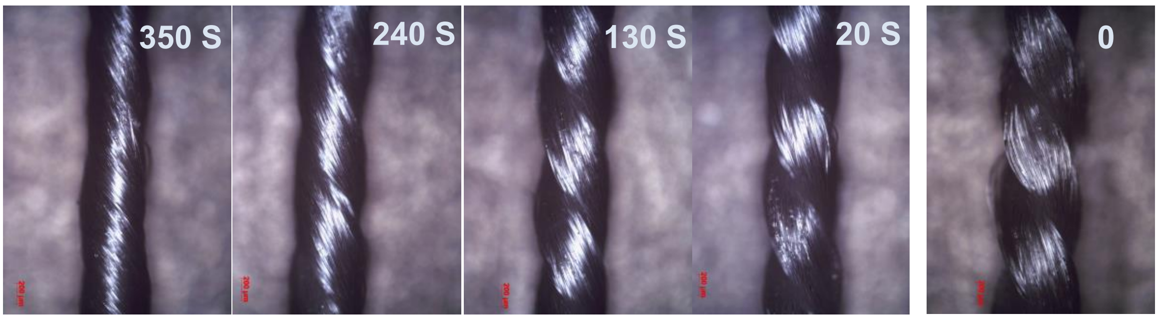


Figure 28 - Microscopic pictures for each cord with high twist level and balanced yarns. (5x magnifications)

Several studies have been done to improve the fatigue resistance of polyesters.[10] It is known that the increase of twist levels causes a higher resistance to the fatigue, but their disadvantages make these cords less attractive. The disadvantages are mainly low strength, high damages on the filaments and high cost construction, because the filaments are more compact/dense.[27]

The damages are caused by the high twist level either applied to the cord or the yarns. Figure 29 illustrates by ascending order the damages caused on yarns < cord < cord and yarns, also is represented on the pictures the twists applied as: initial yarn twist -> final yarn twist – cord twist.

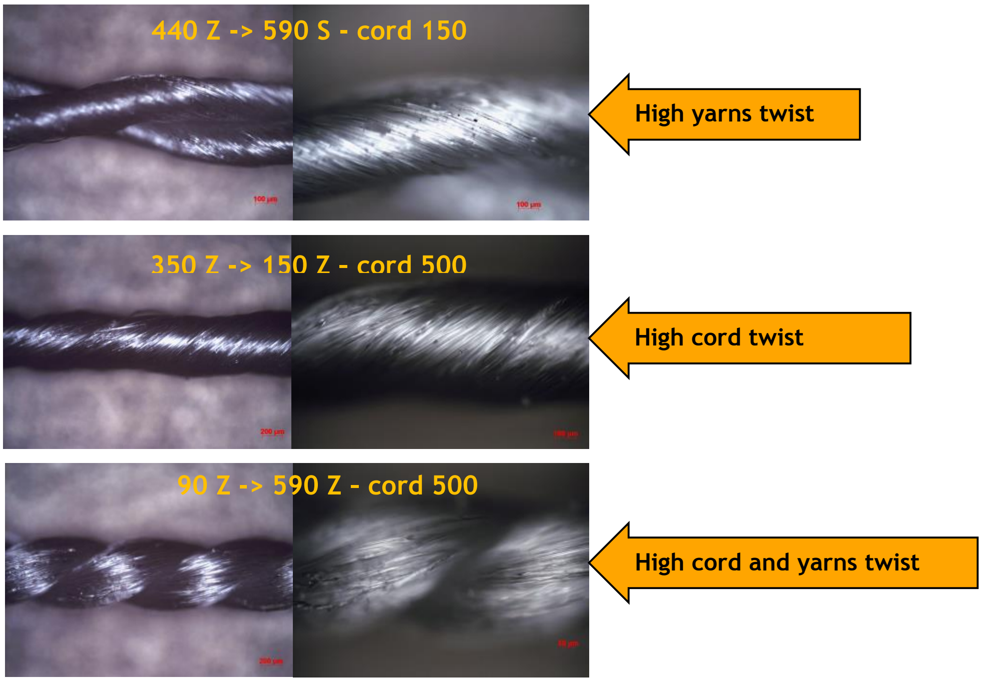


Figure 29 – Microscopic images from cords with damages caused by the high twist in the filaments, with magnifications of 5x and 10x from left to right, respectively.

The high twist causes to a higher friction and tension applied on the yarns, resulting in thin places, in other words weak places and breaking points.[16]

The study of twist level for polyester greige cords was completed and as it was mentioned before, one can conclude that there is a dominant influence of the cord twist over the yarn twist level. For low cord twist level the range of values of elongation, $\Delta\varepsilon$, is 6.6 % and for the breaking force ,$\Delta\sigma$, is 20 N, for medium twist is $\Delta\varepsilon$=2.5 % and $\Delta\sigma$= 10 N, and for high twist level is $\Delta\varepsilon$=0.8 % and $\Delta\sigma$= 8 N; as it may be observed in the following figures:

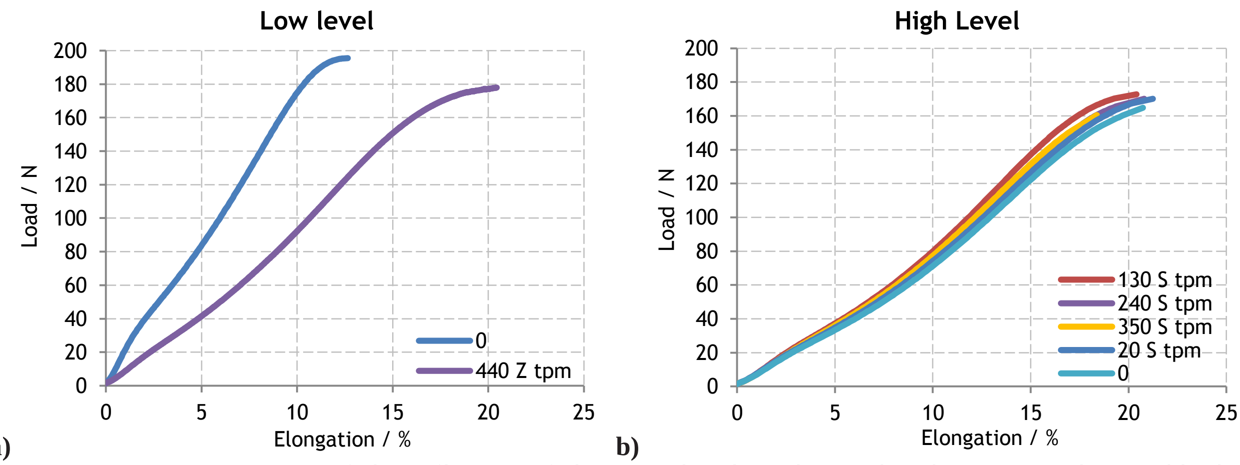


*Figure 30 - Representation of the influence of the twist level on the cord and respective low and high twist level on both plies; **a)** cord with 150 tpm **b)** cord with 500 tpm.*

An important step on the cord production is the dipping process; some experiments performed included this step and the results are presented next:

4.1.3 Dipping Process

The cord without treatment will not adhere to the rubber, to overcome that the cord is subject to dipping process and a sequence of heat and stretch. The heat and stretch rearrange the morphology of the material, is also known as thermo-mechanical process and increases the crystalline phase creating a memory on the amorphous phase. This process allows shrinkage properties on dipped cord.
It was observed that the shrinkage of the greige cords increase with the increase of twist level, but for dipped cords, the same was verified for the dipped cord but it was less evident because the polyester used is a HMLS; high modulus low shrinkage. This feature was not evaluated for the cords dipped since it has a low shrinkage; % of shrinkage during the heat exposure.

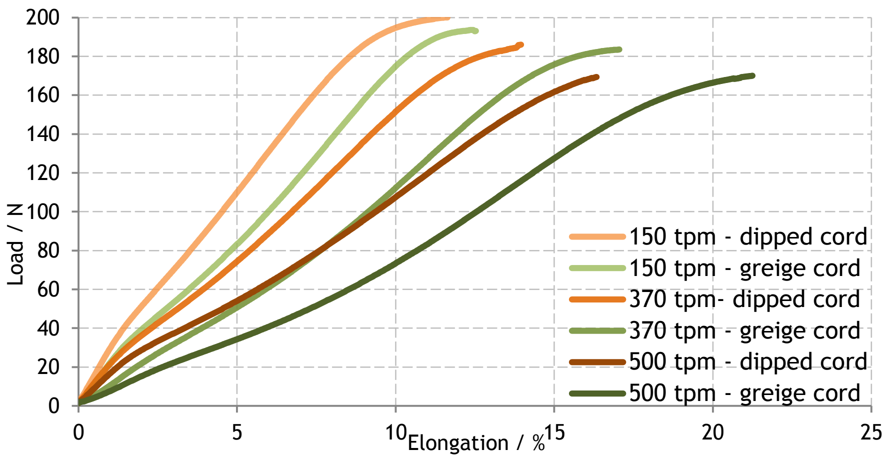


Figure 31 – Relation between dipped and greige cords for the balanced cord construction.

As observed before, the increase on the twist level makes the cord stiffer. The dipping process on those cords, high twist, presents a significantly loss on elongation which is one of the best features. Despite this the strength does not change significantly. One can conclude that the higher the twist levels on the cord the higher the variation of elongation before and after the dipping process, Figure 31.

Figure 32 presents the differences on the cord, before and after the dipping process. On the dipped cords the filaments are closely aligned, also is visible the thickness reduction.

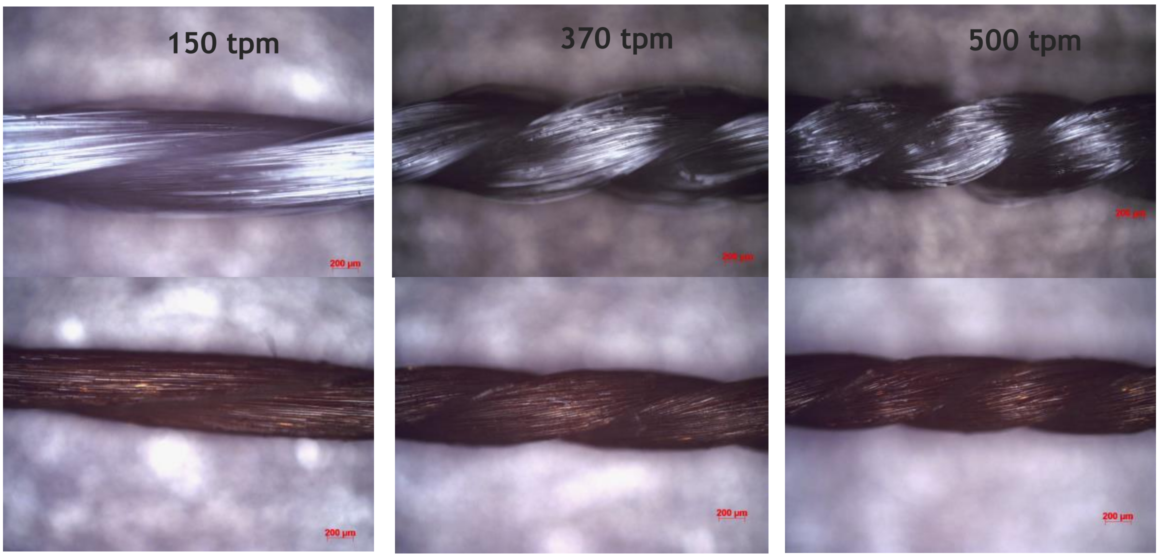


Figure 32 – Microscopic images of greige (top) and dipped (bottom) cords with balanced construction, with low, medium and high twist (from left to right).

The effect of twist in one or both yarns was also studied and it was defined to only choose limited number of cords to impregnate because the short time of work development (dipping process). Besides the cords with balanced construction presented before, two more were selected. The cords chosen were the cord with asymmetric yarn construction and a cord with balanced yarn construction. The cords with high twist level gives a better comprehension once they are more affected by the dipping process, also the look of the cord factor choice; one of the cords looks like just one yarn the other yarn loops around this yarn.

The Figure 33 presents the constructions with balanced cord twist, in blue, cord with balanced yarns, red colors, and the yarns with asymmetric construction, in green.

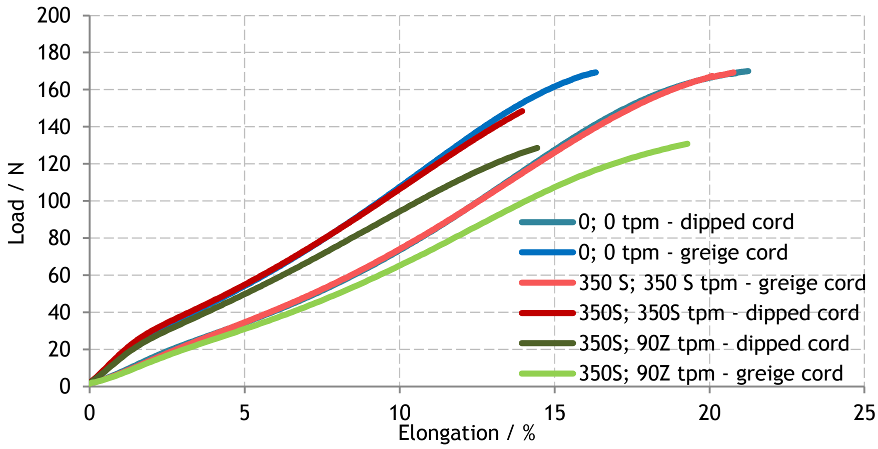


Figure 33 – Greige and dipped cords for cords with 500 tpm, two of them with same twist level for both plies and other with 90Z and 350S tpm on each ply.

The results show that the impregnation does not affect the tensile strength however the elongation affects in a high degree than it was expected for the asymmetric yarns - trial (350 S, 90 Z, 500). On the other hand, the cord with balanced yarns is highly affected resulting in a significate decrease in breaking force and elongation at break. Figure 34 indicates that the shape of the cord, looking as a single yarn, may be the cause for such disparity of values before and after the dipping process.

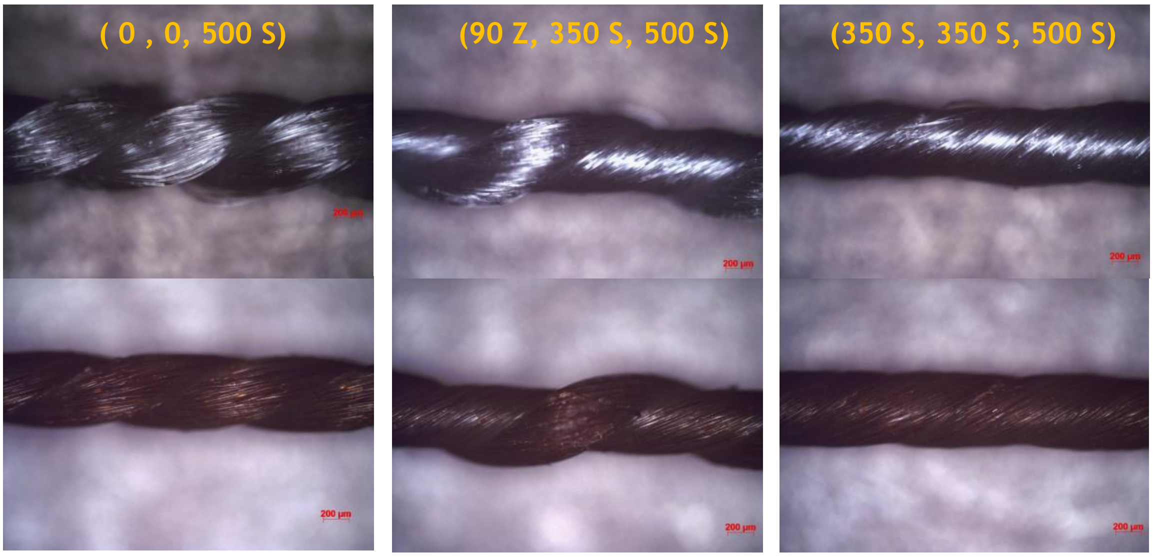


Figure 34 – Microscopic images of the greige and dipped cords presented at for cords with 500 tpm; for balanced and asymmetric cord construction.

4.1.4 Comparison between polyester and nylon

Aytac et al (2009) studied the effect of twist level on tire cords performance for the materials PET and nylon 66, for cords with balanced construction. It was decided to do an extra work to confirm the same results in terms of behavior of the materials for balanced construction.[28] In addition, some extra trials were done to confirm that the nylon has the same behavior of the PET when is twisted with an asymmetric construction.

Figure 32 presents load-elongation curves for nylon and polyester cords with balanced cord construction:

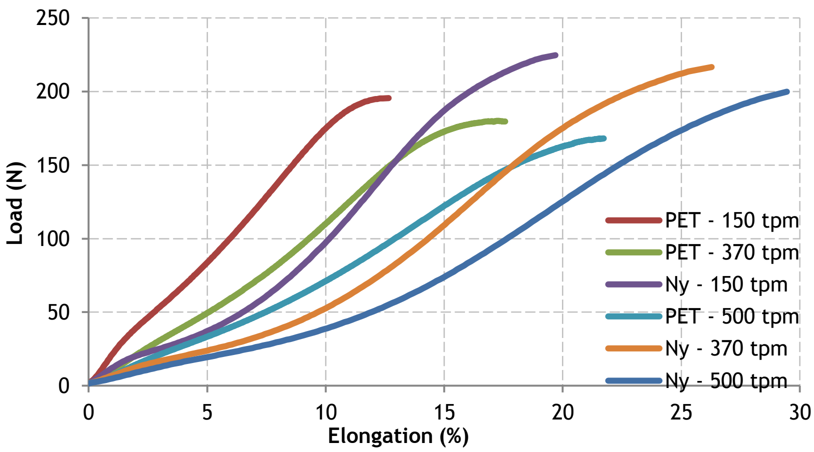


Figure 35 –Load-elongation curves of nylon and polyester greige cords with balanced construction.

The results for nylon show the similar trend of PET material presented in chapter 4.1.1. Table 6 contains the experimental data obtained through the tensile tests performed for both materials and the results confirm the relation of with the increase of twist level. The values of breaking force and elongation at break are higher for the nylon cords because of the crystalline orientation of the nylon, nylon fibers contains more amorphous regions in comparison with the polyester and that configures high values of elongation and breaking force.

Table 6 – Results from tensile tests performed for the balanced cords of nylon and PET.

	Polyester		Nylon	
Cord twist (tpm)	Breaking force (N)	Elongation at break (%)	Breaking force (N)	Elongation at break (%)
150 tpm	196 ± 1	12.7 ± 0.1	225 ± 1	19.7 ± 0.3
370 tpm	180 ± 1	17.0 ± 0.3	217 ± 3	26.3 ± 0.5
500 tpm	164 ± 4	21.2 ± 0.9	200 ± 3	29.4 ± 0.7

Figure 36 show the comparision between the nylon and PET cords with a balanced yarn construction and cord twist with 370 tpm. The legend of the figure is ordered by the reading order of the curves from left to right. The best case study to campare the changes occured in the cords with different yarn twists so it was only performed the the ones with medium twist. The changes of yarn twist shifts the curve in the same points of the curve; a high twist on the yarns causes a high distance between the curves of this cords (220 Z tpm).
Overall, the the behavior of the trials is the same, with only a small difference on the trials 70 S and 110 S tpm, which can be explained by the applied twist on the yarns is closer.

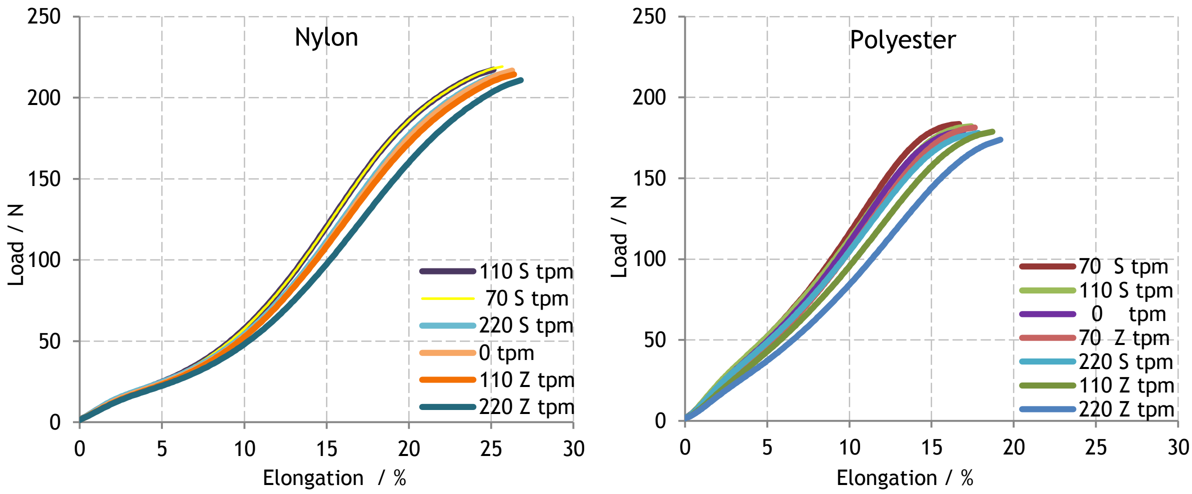


Figure 36 – Load-elongation curves o nylon and Polyester with balanced yarn construction.

It was possible to prove that the response to the variable yarn twist is the same for nylon and polyester.

4.2 Twist direction study

As performed so far, the common practice is the twist-against-twist on the cord manufacturing, but at this section the cords were achieved by changing the twist direction and the twist level, resulting in asymmetric cords. It was used the construction with Z direction for only one yarn and S direction for the other yarn and cord; it was changed the twist level.

Firstly, to prove the construction twist-against-twist Z direction for plies and S direction for the cord is the same as having the construction S for plies and Z direction for cord, the results are presented next:

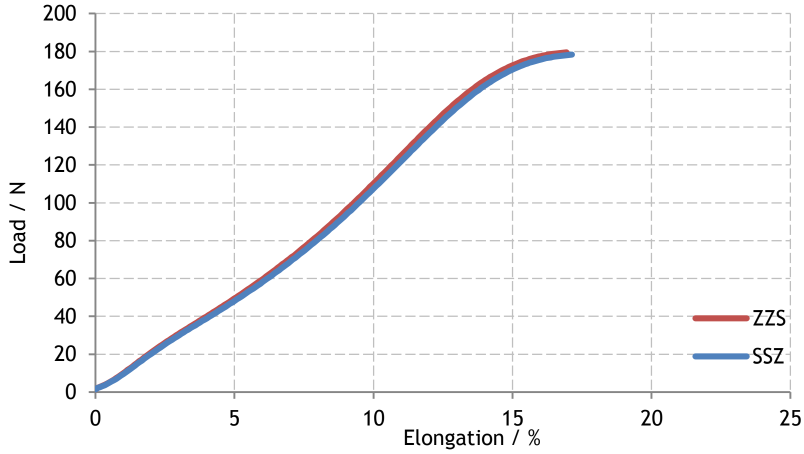


Figure 37 -Load elongation curves of cords with opposite direction construction.

In Figure 37 the cords have a balanced construction with the production values of twist; 370 tpm but different twist direction. It is possible to observe there is no difference on the values of load and elongation.

Figure 38 and Figure 39 show the resulting curves for the study done on cords with low and medium twist level, changing the direction in one or both yarns. Table 7 presents the correspondence of the twists applied on yarns and cord:

Table 7 –Correspondence of twists on the yarns, defined initially and after the cord construction, for cords with twist-on-twist process.

Cord twist (tpm)	Initial yarn twist (tpm)	Final yarn twist (tpm)
150 S	150 Z; 150 S	0 ; 300 S
150 S	150 S; 150 S	300 S; 300 S
370 S	370 Z; 370 S	0 ; 740 S
370 S	370 S; 370 S	740 S; 740 S

In Figure 38, the cords achieved with the twist-on-twist construction on both yarns are represented in blue, light and dark:

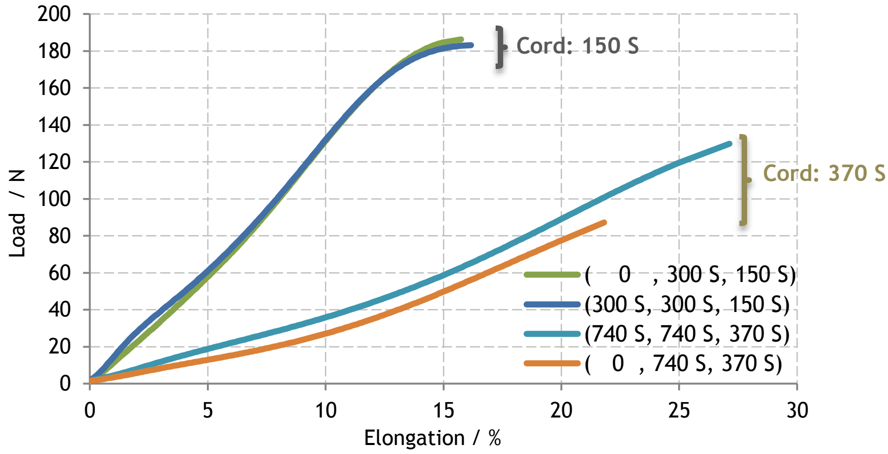


Figure 38 –Load elongation curves of cords with construction twist-on-twist in one or two plies, for cords with 150 tpm and 370 tpm.

An analysis on cords with low level (150 tpm) shows that differences between the cords are mainly with the appearance. The same is not observed for the cord with medium level, 370 tpm, because the modulus decrease significantly caused by the increase of elongation, however, the cord with only one yarn twisted with the same direction of the cord exhibits a worst performance.

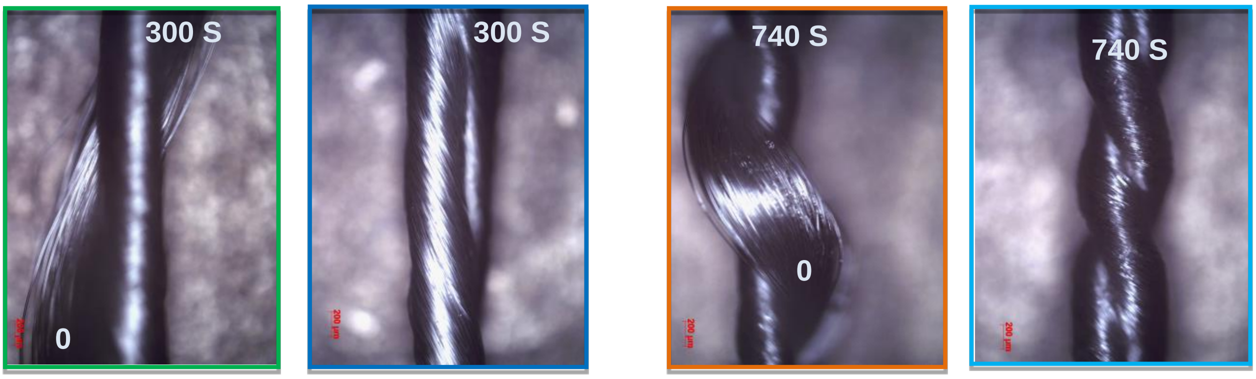


Figure 39 –Microscopic images of the cords performed and presented at Figure 38.

In Figure 39, the color of each cord image corresponds to the color represented on the legend of the Figure 38.

All cords are unstable and it is was observed that without pretension the cords curls up. This effect is denominate as curling effect since the yarn(s) are twisted in same direction of the cord, Annex 3. The fibers will lay at a steeper twist angle, and the cord will be compacted to a smaller diameter. In this type of construction the yarns or cord are hard to the touch. The advantages of those cords are the higher elongation, resistance to fatigue and energy to rupture. However, this construction is not suitable for the industry of textile reinforcement materials because after the dipping process the cord suffers a high decrease on the feature elongation; also the instability of would bring problems related with the weaving process.

The experiments with high twist and twist-on-twist construction were done but it was not possible to execute the tests because the curling effect was too high.

Figure 40, is presents three curves that represent the change done only in cord. As show at Table 8, the two yarns have opposite directions and, at the end, its direction is the same.

Table 8 –Correspondence of twists on the yarns, defined initially and after the cord construction, varying only the cord twist.

Cord twist (tpm)	Initial yarn twist (tpm)	Final yarn twist (tpm)
150 S	150 Z; 150 S	0 ; 300 S
260 S	150 Z; 150 S	110 S; 410 S
370 S	150 Z; 150 S	220 S; 520 S

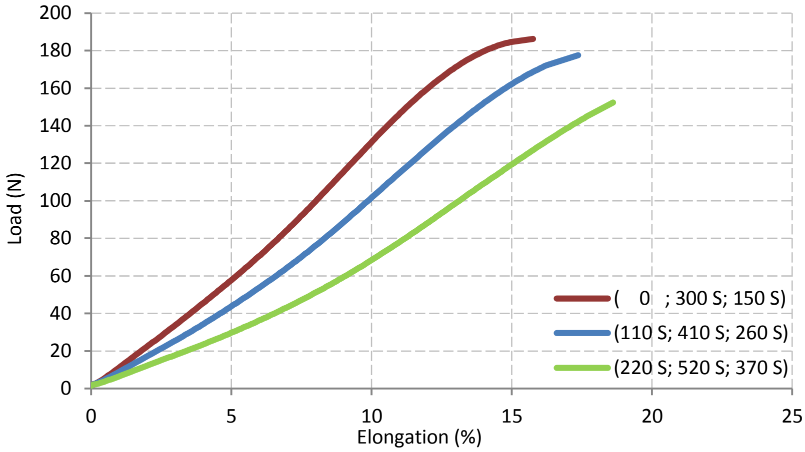


Figure 40 –Load elongation curves of cords with asymmetric construction varying only the cord twist

Is possible to observe that with the increase of the cord twist changes significantly the twist of yarns because of the initial twist applied, one of the twist ply is being incremented. Despite being incremented each yarn and cord 110 tpm there is a larger distance from the other curves and a tendency to a linear curve for the cord 370 tpm, represented in green. Figure 41 shows the appearance of those cords and it is observed that the cord 370 S is more compressed and it is not notorious the difference of twist of the yarns unlike the others. The likely cause of a lower breaking force and elongation at break than expected for this cord is that a high compression of the filaments and consequent high plies bonding.

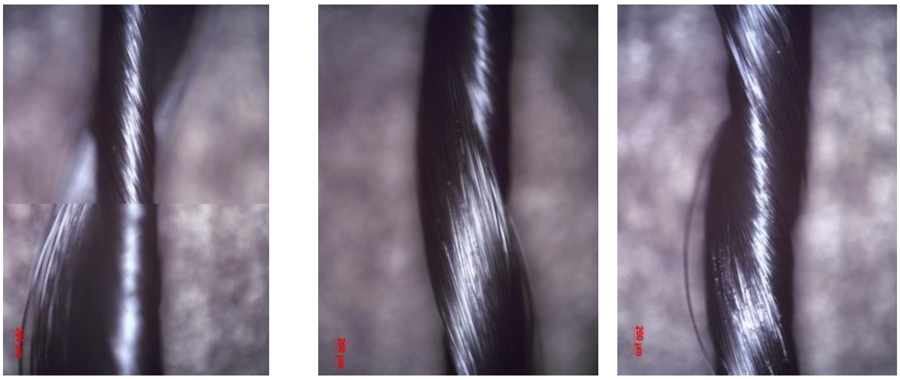


Figure 41 – Microscopic images of cords with asymmetric construction varying only the cord twist.

More trials were performed but the results were inconclusive or cord construction impracticable or the cords were unstable due to snail formation. The snail effect is characterized for having one ply with an excess of length in comparison with the other, Annex 3.

4.3 Response surface methodology and results prediction

Response surface methodology is a collection of mathematical and statistical techniques based on the fit of a polynomial equation to the experimental data generating the lowest residual possible and describes the behavior of a data set with the objective of making statistical previsions. The parameters are estimated using the method of least for square and selecting the adequate experimental design.[21] As it was mentioned before, the experimental design resulted in 15 experiments as is show at Table 10. The process responses chosen to analyze in this section are the breaking force (σ_{break}), elongation at break (ε_{break}) and elongation at 45 N ($\varepsilon_{45\ N}$) for the parameters yarn 1, yarn 2 and cord twists. Those parameters are the points that characterize the curve load-elongation.
In this chapter it only was done the statistical model prediction for the cord with the construction with Z direction on yarns and S direction on the cord.

Table 9 - Parameters and levels considered in the design of experiments.

Factors	Level		
	1	2	3
Yarn 1	150	370	590
Yarn 2	150	370	590
Cord	150	370	500

The software used to evaluate the effect of independent variables on the process performance was JMP 11.0.0 (SAS software) and it was possible to fit models of second order for the results from the factorial experiments. The equation for the generic parameter process response is:

$$\boldsymbol{y} = \boldsymbol{a_0} + \boldsymbol{a_1}\, m_{yarn\,1} + \boldsymbol{a_2}\, m_{yarn\,2} + \boldsymbol{a_3}\, m_{cord} + \boldsymbol{a_4}\, m_{yarn\,1} \times m_{cord} + \boldsymbol{a_5}\, m_{yarn\,2} \times m_{cord} + \boldsymbol{a_6}\, m_{yarn\,1} \times m_{yarn\,2} + \boldsymbol{a_7}\, m_{yarn\,1} \times m_{yarn\,2} \times m_{cord} \qquad (4.1)$$

Where y is the process response; $m_{yarn\,1}$, $m_{yarn\,2}$ and m_{cord} are the process factors, in tpm; $\boldsymbol{a_0}$ is the interception coefficient; $\boldsymbol{a_1}$, $\boldsymbol{a_2}$ and $\boldsymbol{a_3}$ are the equations coefficients related to the factors effects; $\boldsymbol{a_4}$, $\boldsymbol{a_5}$ and $\boldsymbol{a_6}$ correspond to the cross interaction between factors. Not all p-values (Prov > F) of t-Student test for the predicted responses of each parameter are lower than 0.05; that indicates a weaker indication of the model's significance. On the other hand, determination coefficients (R^2) vary only between 0.923 and 0.958, indicating that the models can explain largely the experimental variance. It was observed that models fit, but for the parameter breaking force the influence of yarn 1 is marginal once the p-value obtained is higher than 0.15, for the same reason, the factor yarn 1 combined with cord factor has a marginal influence on the model for the parameter elongation at 45 N.[29]

The equations 2, 3 and 4 results from the removal of negligible parameters:

$$\boldsymbol{\sigma_{break}}\ (\boldsymbol{N}) = 205 + 1.23 \times 10^{-2}\, m_{yarn\,1} + (-2.59 \times 10^{-2})m_{\text{yarn 2}} + (-6.81 \times 10^{-2})m_{cord} + (m_{yarn\,1} - 355)((m_{cord} - 340) \times (4.30 \times 10^{-4})) + (m_{\text{yarn 2}} - 385)((m_{cord} - 340) \times (-2.54 \times 10^{-4})) \quad \textbf{\textit{(4.2)}}$$

$$\boldsymbol{\varepsilon_{45\,N}}\ (\%) = 9.52 \times 10^{-1} + 1.28 \times 10^{-3}\, m_{yarn\,1} + 2.46 \times 10^{-3}\, m_{yarn\,2} + 7.92 \times 10^{-3}\, m_{cord} + (m_{yarn\,1} - 355)((m_{cord} - 340) \times (-1.39 \times 10^{-5})) + (m_{yarn\,2} - 385)((m_{cord} - 340) \times (-1.29 \times 10^{-6})) \quad \textbf{\textit{(4.3)}}$$

$$\boldsymbol{\varepsilon_{break}}\ (\%) = 10.8 + 3.99 \times 10^{-3}\, m_{yarn\,1} + 4.12 \times 10^{-3}\, m_{yarn\,2} + 1.19 \times 10^{-2}\, m_{cord} + (m_{yarn\,1} - 355)((m_{cord} - 340) \times (-8.33 \times 10^{-6})) + (m_{yarn\,2} - 385)((m_{cord} - 340) \times (-2.06 \times 10^{-5})) \quad \textbf{\textit{(4.4)}}$$

These models can be used to interpolate predicted values and compare them with the experimental ones. Figure 42 compares the experimental with the predicted/fitting data for all responses. The parity plots show that the experimental data is close to the predicted curves and the coefficients R^2 are close to the unit meaning the proximity on the predicted and observed values.

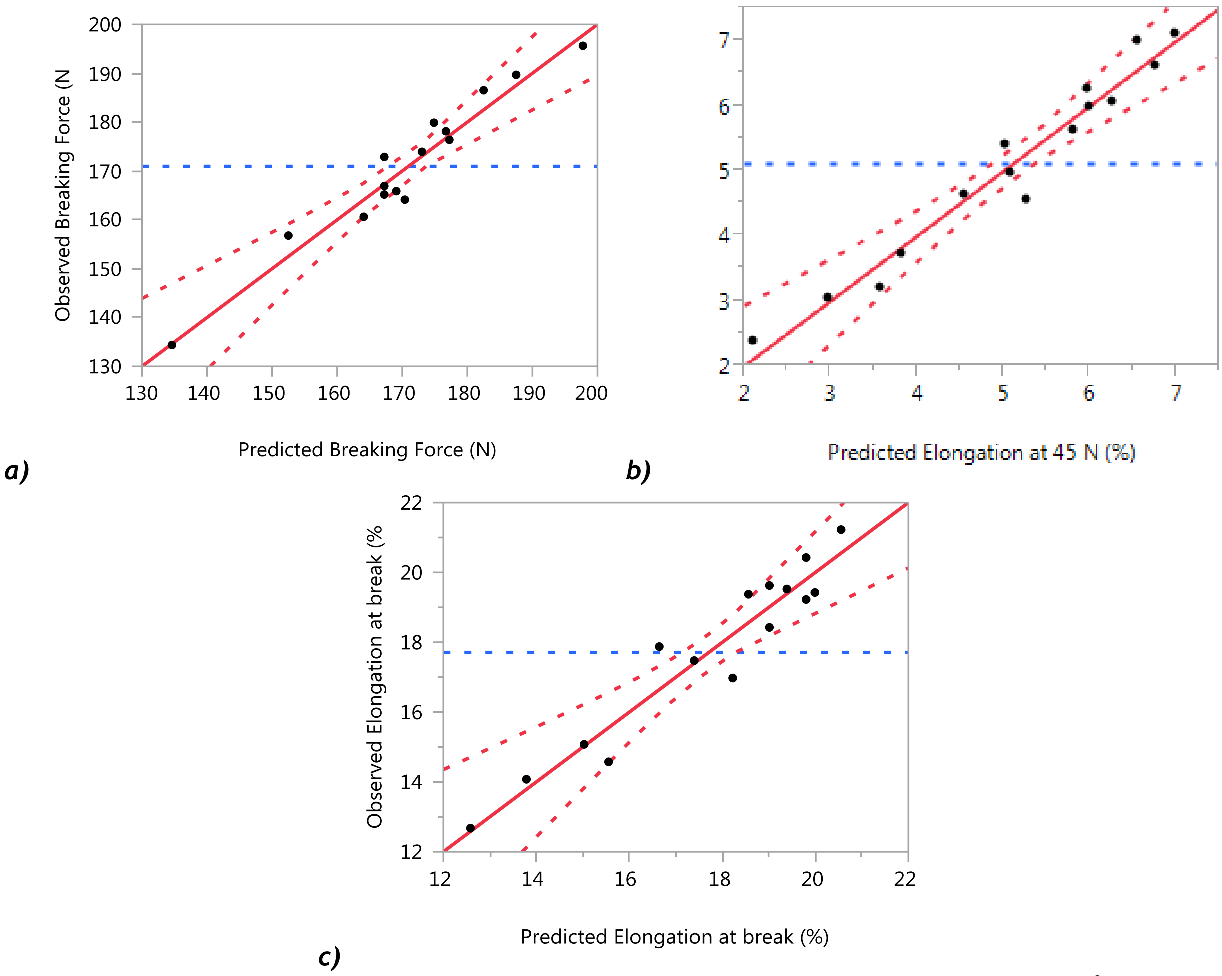


Figure 42 - Comparison between predicted and experimental values: a) breaking Force (R^2= 0.945), b) elongation at 45 N (R^2= 0.958) and c) Elongation at break (R^2=0.923).

Table 10 summarizes the results obtained with the factorial design and the results obtained from the fitting models (equations 2, 3 and 4). Not all results fit in the prediction models

Table 10 – Combination of experiments used to predict the model and Values observed and predicted for the parameter in study.

Run levels	Factors			Breaking Force (N)		Elongation at 45 N (%)		Elongation at break (%)	
	Yarn 1	Yarn 2	Cord	Observed	Predicted	Observed	Predicted	Observed	Predicted
111	150	150	150	196	198	2.40	2.10	12.7	12.6
211	370	150	150	186	183	3.05	2.97	14v0	13.8
221	370	370	150	189	188	3.21	3.56	14.6	15.6
311	590	150	150	165	167	3.74	3.83	15.0	15.0
331	590	590	150	176	177	5.41	5.02	19.3	18.6
112	150	150	370	178	177	4.63	4.54	17.9	16.6
122	150	370	370	166	169	4.98	5.07	17.4	17.4
222	370	370	370	180	175	4.55	5.26	17.0	18.2
232	370	590	370	167	167	5,64	5.80	19.6	19.0
332	590	590	370	174	173	5,98	5.99	19.2	19.8
113	150	150	500	160	164	6.27	5.98	18.4	19.0
133	150	590	500	134	135	7.12	6.97	19.5	19.4
223	370	370	500	173	167	6.07	6.27	20.4	19.8
233	370	590	500	157	153	6,63	6.77	19.4	20.0
333	590	590	500	164	171	7.00	6.56	21.2	20.6

The models can be used to interpolate the effect of different twist values on the parameters breaking force, elongation at break and elongation at 45 N. Some in-between values were used to confirm the models fitting as show at Table 11.

Table 11 - Confirmation trials for the fitting models presented, equation 2, 3 and 4.

Factors			Breaking Force (N)		Elongation at 45 N (%)		Elongation at break (%)	
Yarn 1	Yarn 2	Cord	Observed	Predicted	Observed	Predicted	Observed	Predicted
260	260	150	192	193	3.05	2.83	14.0	14.1
480	480	150	181	182	4.16	4.29	17.2	17.1
260	260	370	182	176	4.26	4.90	17.4	17.4
300	300	370	184	175	4.30	5.03	16.7	17.7
440	440	370	181	174	4.88	5.49	17.6	18.7
480	480	370	179	174	5.25	5.63	18.7	19.0
260	370	370	181	172	4.41	5.17	17.0	17.8
480	370	370	179	178	4.86	5.36	18.3	18.7
260	590	500	170	144	6.35	6.87	19.8	19.7
480	590	500	170	162	4.86	6.66	21.3	20.3

Table 11 show the experimental and predicted values of the process response, according with the equations of the fitting models. Most of predicted values present a satisfactory results with small deviations from the experimental data.

Figure 43 and Figure 44 show the surface profiles of the breaking force and elongation at break, respectively. It is possible to conclude that the most relevant factor is the cord twist on both parameters, also the relation between both yarn twist is minor, as the models show before. The results are consistent with the observations of the chapter 4.1.

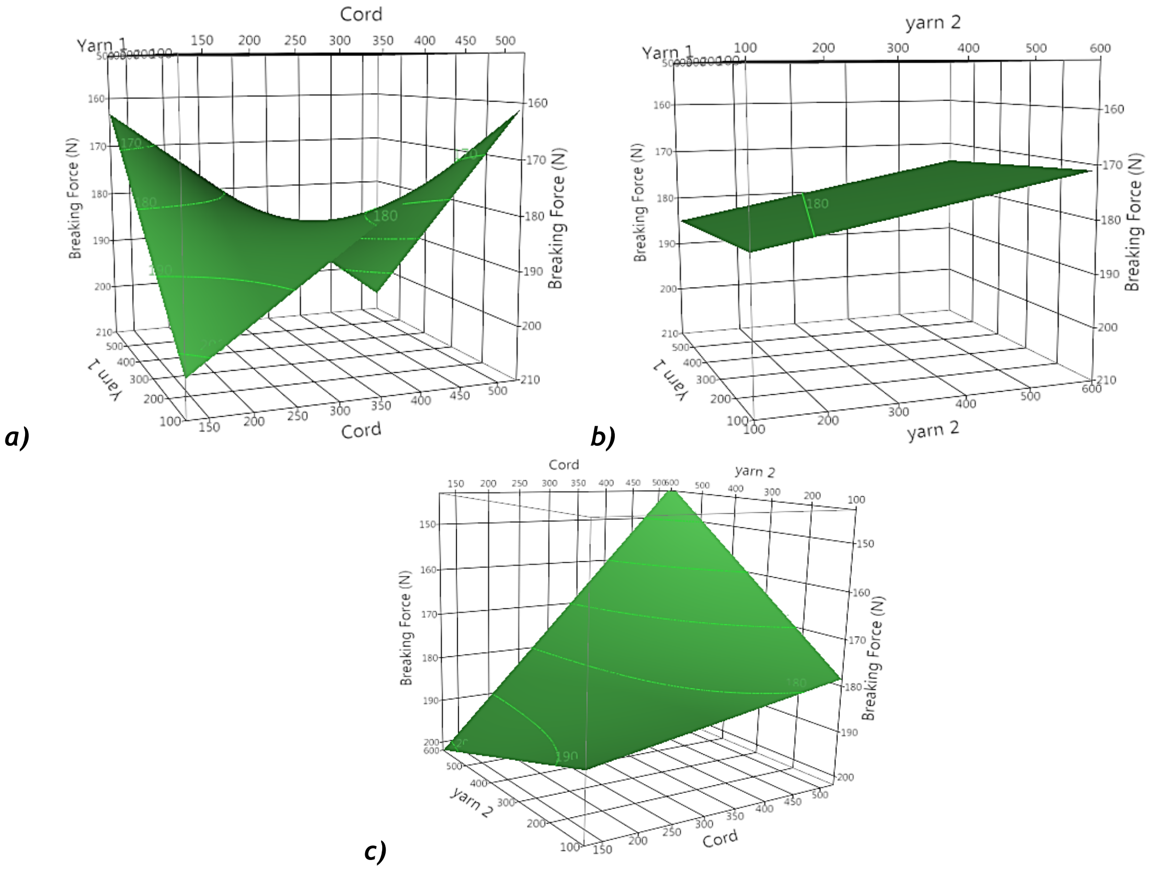


Figure 43 – Breaking force as a function of operating conditions: a) yarn 1 and cord, with yarn 2 constant; b) yarn1 and yarn 2; c) yarn 2 and cord.

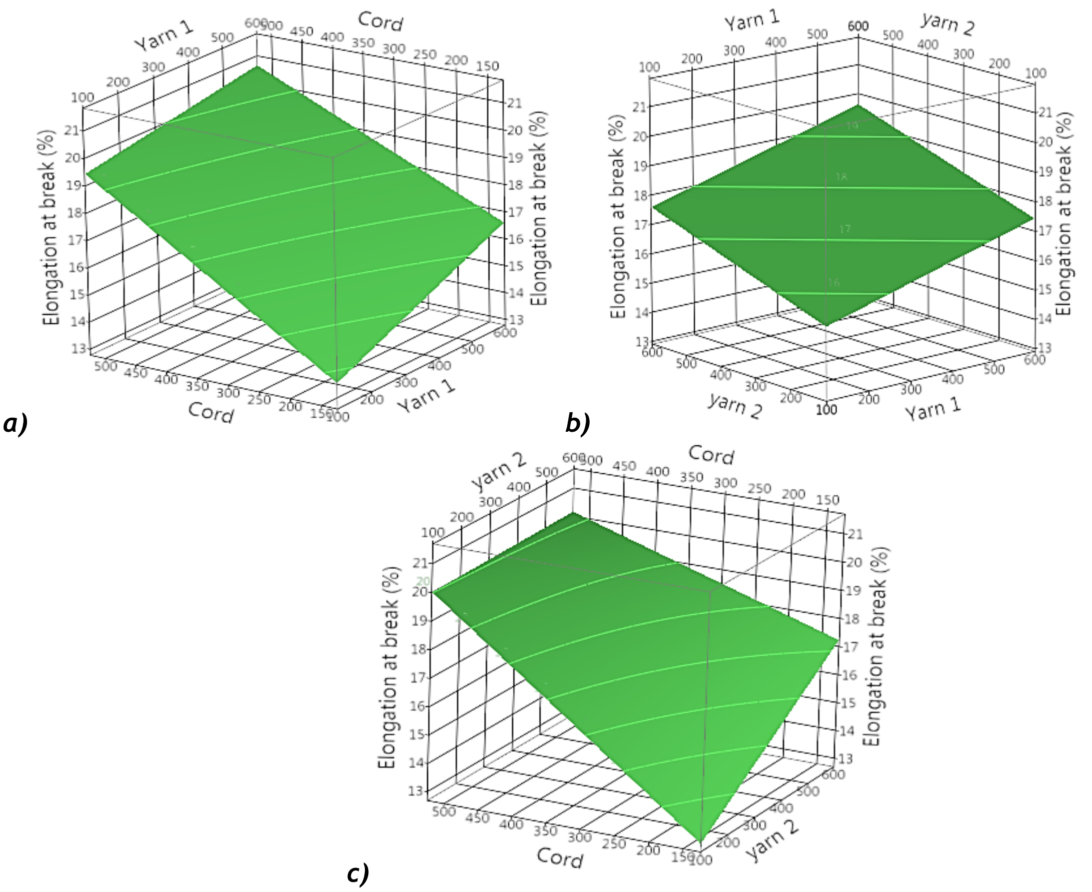


Figure 44 – Elongation at break as a function of operating conditions: a) yarn 1 and cord, with yarn 2 constant; b) yarn1 and yarn 2; c) yarn 2 and cord.

It is possible to optimize the operation condition by a desirability function of JMP software for all the parameter, Annex 4. The criteria used was maximized for the three variables and the optimal operations were found to be 590 tpm for yarn 1, 150 tpm for yarn 2 and 500 tpm for cord and the results of each parameters is show next:

Table 12– Predicted optimal results with respective variation and experimental results.

Response	Predicted values			Experimental values
	Predicted	Min	Max	
Breaking force (N)	200	186	213	134
Elongation at 45 N (%)	5.56	4.38	6.74	7.12
Elongation at break (%)	20.2	17.5	23.0	19.4

The optimization is not consistent because the values obtained do not correspond to the real values; it is observed a disparity between the result predicted and experimental result. As observed before, a cord with the combination (150 Z, 590 Z, 500 S) is weak and unstable.

5 Conclusions

This thesis concerns the characterization of load-elongation curves behavior of asymmetrically twisted cords for tire reinforcements, as so as properties of breaking force, elongation at break, thickness and yarn/cord angles. A laboratory twisting unit was used to construct the cords were the variables of twist level and direction were defined.

The results of this work provided two major conclusions: In first, the method two-for-one influences the shape and the properties of the cord because a high initial yarn twist applied introduces damages on the filaments. A construction where yarn(s) and cord have the same direction (twist-on-twist construction) it is possible to obtain more twists on the yarns and benefit with a lower damaging effect comparing with the regular construction. It is not possible to construct cords with the twist-on-twist construction when just one of the yarns and the cord have the same construction direction and the twists of the yarns are significantly different from one another.

In second, the influence of the yarn twist only is significate when the cord twist is low. Analysis on the shape of the curves load-elongation showed the factors that change the different sections of the curve; the elastic region is significantly changed when the twist on the cord is increased or when the cord has a low twist and it is changed the twist of the yarns. The plastic region of the curve is changed on the second half if the cord or yarns have a high twist level or if the difference of twist on plies is significant.

The cords performed showed that higher twists allows a cord to behave as a spring that will not open up under compression, while lower twists allow a cord to behave as a rod, maximizing the strength. In opposite, high degree of twist damages the fibers and reduces the tensile strength of the cord.

The study of nylon and polyester materials confirmed the results of studies published, where both materials presents the same behavior. The polyester study showed for balanced cords that the increase of the twist level on the cord provides an increase on the elongation however it loses on the breaking force property. The increase of twist level results too on the increase of angle and density of the cord.

In what concerns to the study of polyester material, a percentage increase of 44 % (150 to 370 tpm) on the cord twist level relative to the total amount applied on the cord (500 tpm) results in a decrease of 8% on the breaking force and an increase of 20 % on the elongation at break. When the increase is from 150 to 500 tpm the percentage of increase is not the double however it results in a decrease of the breaking force and increase on the elongation at break of 16% and 40 %, respectively.

A high elongation might be advantageous for the tire because it makes more resistant to the fatigue, though it implies the loss of strength, damages of the filaments and the increase of the cord cost construction.

The results proved by doubling the quantity of filaments the breaking force value doubles too concluding that the decitex of the cord influences highly the values of breaking force.

6 Project Assessments

6.1 Accomplished Objectives

The objective of this work was the characterization of the properties of asymmetric cords. It was defined to modify the construction of the cords by changing the twist level of the yarns and cord, and the twist direction. The material in study was polyester but it was possible to change the variable yarn material on this study, and the nylon material was introduced to the study.

The collection of the data resulted in a prediction equation that describes the values obtained for breaking force and elongation at break with the twist levels applied on yarns and cords.

6.2 Limitations and Future Work

The limitations of this work are related mainly with equipment, as the number of twist that could be applied on the cord, and time of experiments.

In the future it is recommended to study the response of twist level and direction on the remaining materials. Also, introducing the study of the resistance to fatigue of the cords would allow understanding the impact of having the plies with different twists.

Hereafter, it might be interesting to explore the asymmetric construction for yarns with different linear density or yarns with different materials, hybrid cords. This study may show if the difference of twists on the yarns can balance some properties as elongation and load show the point where the cord is stable, mainly for the hybrid cords. For instance, this study might confirm if a cord with high twist and different linear densities on the yarns can increase the breaking force.

6.3 Final Assessment

The foundations are built, now is necessary to choose the variables that are most important in this section of the cord study.

This project was very interesting to develop, it was rewarding be part of a continuous project that contribute for the knowledge and future development of the performance of the tires.

Personally, it was enriching because all the learning acquired in the industry and with some techniques, also it was possible to improve some personal skills during this time.

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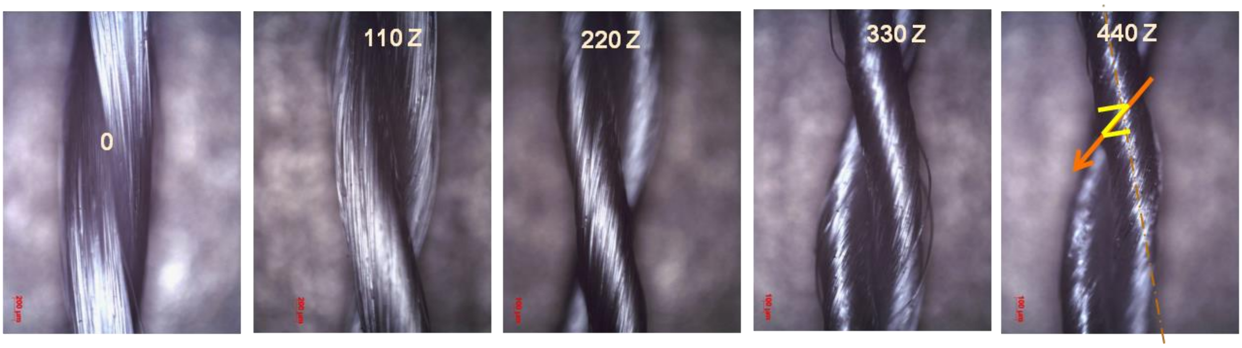
Annex 1. Cord 150 tpm

Twist (tpm)	Helix Angles	
	Cord (°)	Ply (°)
Low	9.4	5.0
Low-medium	12.0	2.2
Medium	12.1	4.4
Medium-high	12.0	15.0
High	12.5	28.0

Cord twist (tpm)	Initial yarn twist (tpm)	Final yarn twist (tpm)
150 S	150 Z	0
	260 Z	110 Z
	370 Z	220 Z
	480 Z	330 Z
	590 Z	440 Z

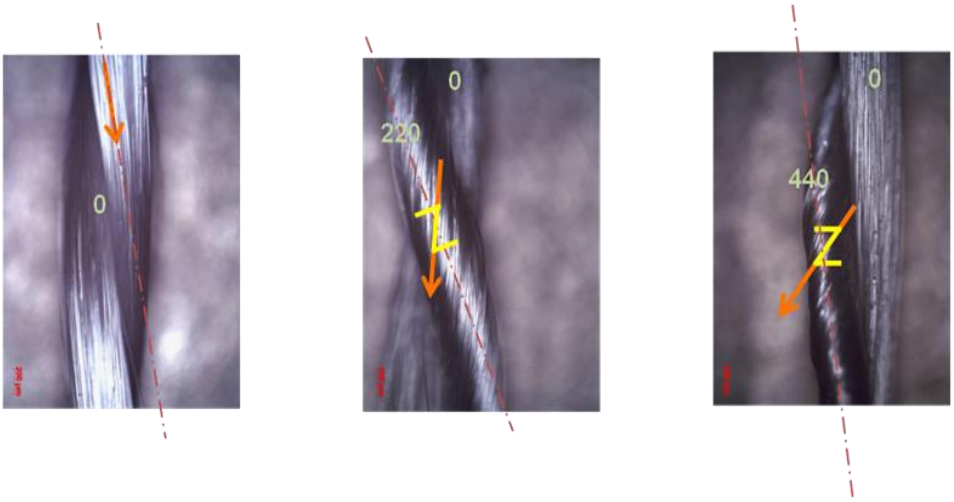
Legend of curves Load-elongation

Cords with balanced yarn construction: initial/final twist (variable, variable, 150 S)



Cords with unbalanced yarn construction: initial twist (variable, 150 Z, 150 S)

final twist (variable, 0 , 150 S)

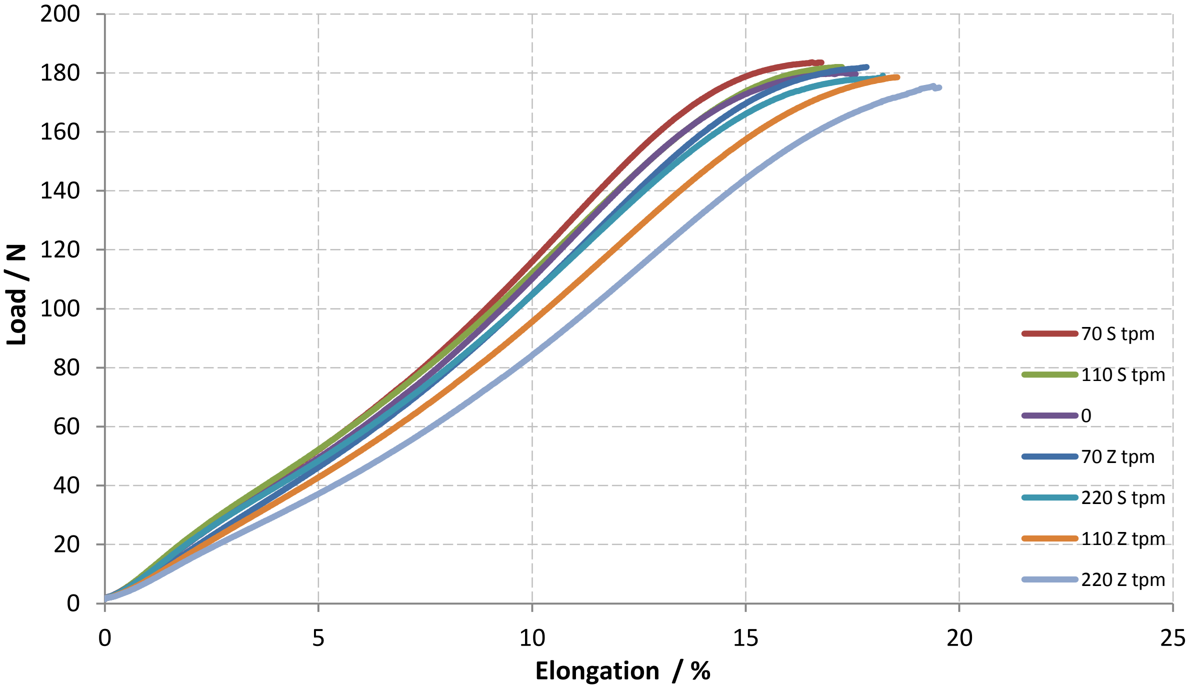


Annex 2. Cord 370 tpm

Correspondence between initial twist and the final twist applied to the yarns, for the cords with 370 tpm.

Cord twist (tpm)	Initial yarn twist (tpm)	Final yarn twist (tpm)
	150 Z	220 S
	260 Z	110 S
	300 Z	70 S
370 S	370 Z	0
	440 Z	70 Z
	480 Z	110 Z
	590 Z	220 Z

Load-elongation curves for cords with 370 tpm and both plies with initial twist 150 S (0) and,590 S (220 Z).

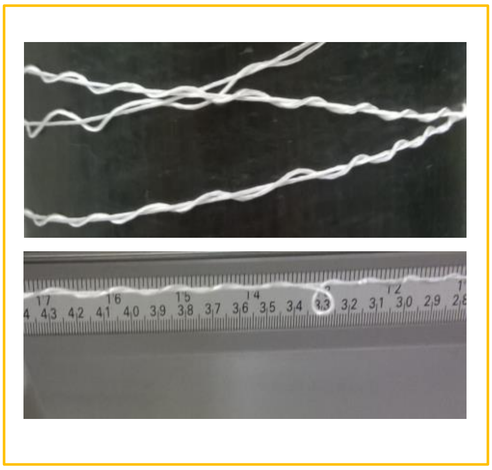


Annex 3. Problems occurred during the twist process

Curling Effect

This effect results from the high twist level on one, two yarn ou cord. There are different levels of curling.

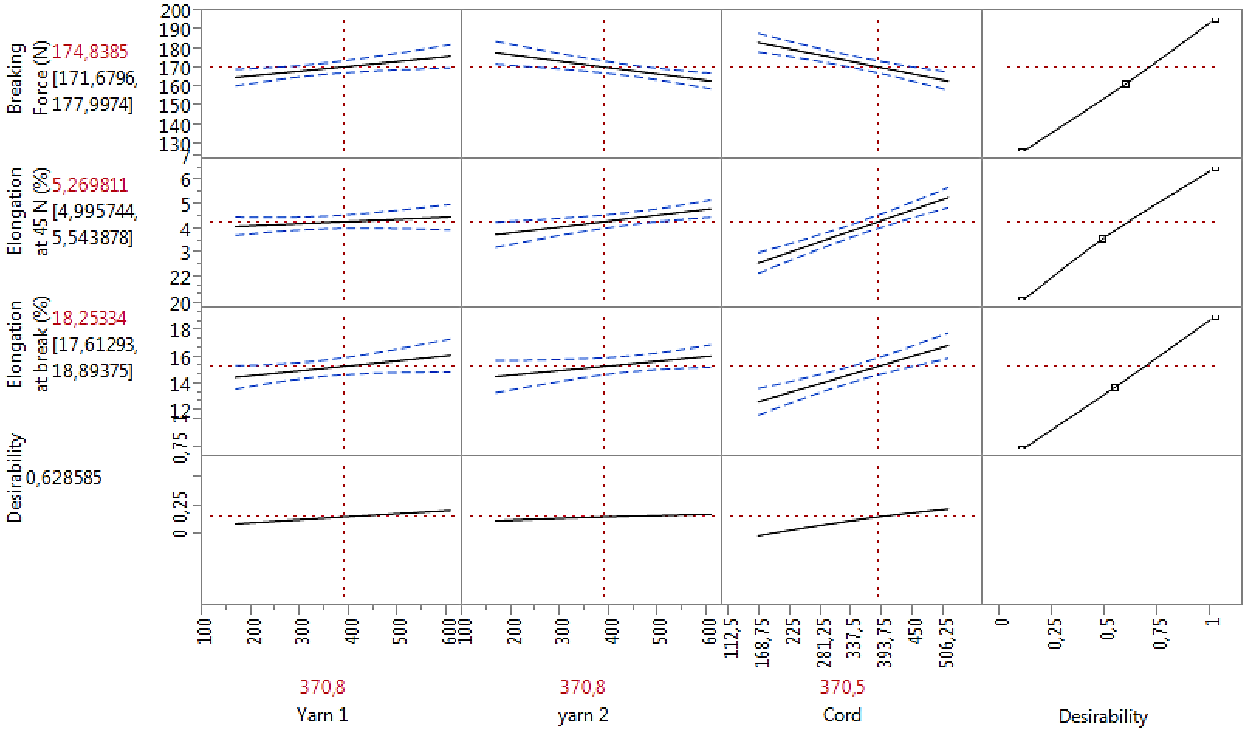
Snail Effect



This effect results from the some types of construction where one of the plies have a high quantity of yarn on the cord, which mean the difference of length of each ply is

Annex 4. Optimization of predicted models

Prediction Profiler



Desirability Maximized: